

Article

The Influence of Effective Mass on the Striking Force of Lead Jab and Rear Cross Punches of Boxers

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Abstract: Background: Modern combat sports, including boxing, categorize participants by body mass to ensure fairness and safety. The effective mass, or the ability to maximize body mass during a punch, significantly impacts striking force. This study aims to explore the relationship between effective mass and striking force in lead jab and rear cross punches of boxers. Material and methods: Thirteen male boxers with an average body mass of 90.6 kg and average height of 184 cm participated. The study employed an AMTI MC12-2K force plate (AMTI, Watertown, MA, USA) and Noraxon Ultium EMG sensors (Noraxon, Scottsdale, AZ, USA) to measure impact force and acceleration. Each boxer performed five maximum-force strikes with both lead jab and rear cross techniques. Results: The rear cross punch generated significantly higher ground reaction force (1709.28 ± 486.62 N) compared to the lead jab (1182.56 ± 250.81 N). However, effective mass values were similar for both punches: lead jab (18.95 ± 5.29 kg, 21.51% of body mass) and rear cross (18.50 ± 5.56 kg, 21.04% of body mass). Higher body mass and longer training tenure positively correlated with higher effective mass. An inverse relationship was found between fist acceleration and effective mass. Conclusions: Effective mass plays a crucial role in punch biomechanics, with similar utilization between lead jab and rear cross punches despite the latter's higher force. Training focused on optimizing body mass utilization and refining punch techniques can enhance punch effectiveness.

Keywords: biomechanics; boxing; effective mass; combat sport



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1. Introduction

As with all modern combat sports, boxing divides participants into body-mass-dependent categories to ensure fairness and safety of athletes. Differences between divisions range from 3 to 6 kg, depending on the weight category, from 46 to 48 kg for flyweight to 92 kg+ for heavyweight. It ensures fair competition—fighters in the ring face each other under identical or very similar physical conditions. They have similar body mass and height, comparable arm length, and reach. Crucially, they are capable of generating similar striking force and accept the risk of receiving similarly powerful blows with respect to the technique used. Variations in the power of punches also depend on the specific punch type—cross, hook, or uppercut—and can develop varying values of impact force and limb acceleration [1]. The effectiveness of a strike is linked not only to the athlete's body mass [2] but also to their technical skill level [3]. Within each category, participants have similar body mass, so they gain advantages in endurance, technical-tactical preparation, and the power of their strikes by utilizing their mass and giving their body segments proper acceleration.

This leads us to the concept of effective mass, which refers to the phenomenon of increasing the effective mass of the body or limb during movement, which can influence the ability to generate force and torque [3,4]. Effective mass, often referred to as “inertial mass”, is the portion of an athlete's body mass that actively contributes to the power of a strike. In the context of boxing, the concept of effective mass is crucial for understanding how a boxer can maximize punch force through optimal utilization of body mass, especially

during a fist strike. A higher effective mass means that more of the boxer's body or limb mass is biomechanically engaged at the moment of impact, thereby enhancing the force delivered to the target. This integration is essential for maximizing punch power, as it ensures that the entire body contributes to the force of the strike, rather than just the arm or fist. Understanding and optimizing effective mass is, therefore, a key component in boxing biomechanics, directly influencing the effectiveness of a punch. Essentially, increasing effective mass means that the boxer's body or limb becomes biomechanically integrated at the moment of contact with the target, potentially enhancing the striking force [2]. There are a few studies, proposing different ways of its computation, but overall understanding of this concept lies in the percentage value of the whole body mass that contributes to the generated force. There can be different ways to achieve it. Initial stance and shift of the body weight, with center of gravity swaying towards a target, can contribute more mass into a strike at cost of stability [1]; stiffening of body segments at the moment of contact with a target to act as a solid block instead of a whip-like movement (which is more demanding and could be obtained only with specific martial art techniques) [2], or integrating more segments into the kinematic chain, forcing more joints to contribute to summary degrees of freedom of movement [5]. Also, biomechanical differences between seemingly identical straight punch techniques like lead jab and rear cross result in the striker achieving varied values of striking force and fist acceleration, which will be reflected in the effective mass coefficient.

In combat sports, effective mass is determined in various ways [3,6]. Some researchers opt for the use of simple momentum conservation models—it is assumed that during a strike on the target, the limb transfers all of its momentum to the target, resulting in its displacement with a measurable velocity [2]. However, the obtained value of effective mass may vary depending on the mass of the target. Therefore, the use of this model is not fully justified. There is also a method that involves the application of a modified form of Newton's second law with the equation " $Me = F_{max}/a$ " [4]. It describes the effective mass (Me) involved in a strike, where F_{max} represents the maximum force with which the strike was performed, and " a " stands for the maximal acceleration before contact with a target. In essence, it quantifies how the effective mass relates to the force and acceleration during the strike.

In sports biomechanics, there is the concept of kinematic chain, which refers to a series of body segments connected by joints. These segments and joints work together to generate movement. Understanding the kinematic chain is crucial for analyzing and improving sports movements [7]. In boxing, every movement, both offensive and defensive, utilizes different elements of the kinematic chain and degrees of freedom. The more muscles are involved in the movement, the greater the total generated force. In the case of a punch in boxing, engaging a greater number of muscles, such as leg, hip, torso, and arm muscles, can lead to increased total generated force. This means that coordinated involvement of multiple muscles in the kinematic chain can contribute to more effective force generation and more efficient execution of boxing technique. A greater degree of freedom in a given movement may result in higher total generated force [1].

Sports biomechanics have reached a state-of-art level of use of measurement equipment, which is composed of capturing spatiotemporal data alongside measuring a force of a strike. Variables such as velocity and acceleration are captured using stereophotogrammetry with systems like VICON [8], or with inertial measurement units (IMUs) [9]. Both systems have their advantages; however, the simplicity of setup with IMUs makes them more and more popular, especially with current improvements of those devices, reaching up to 400 g acceleration capacity, suitable for capturing strike-related data [4]. Force plates measure ground reaction force, but are often customized to be used as a striking areas [4]. This could not be obtained without modifications, as force plates are solid-metal coated. They need to be padded with shields, which leads to differences in initial setups between biomechanics laboratories. Another option is to place shields on beams and use inertia/momentum measurements to compute the force of a strike [10]. Force plates

and motion capture systems can be integrated by syncing them to match the timing of measurement and ensure its accuracy. This solution is popular and allows scientists to explore different concepts of kinesiology phenomena in combat sports, such as the discussed concept of body mass presented in this work.

Observations indicate a correlation between effective mass and striking force [2]. Further examination of this correlation may contribute to a better understanding of the mechanisms shaping the performance of boxers and lead to the identification of key factors influencing the effectiveness of their punches in relation to participant weight. Therefore, this study focuses on the kinetic analysis of straight punches of boxers, taking into account the role of effective mass. The aim of this study is to identify the relationship between effective mass and striking force and understand how effective mass influences the performance of the straight punch technique. The adopted approach will allow a deeper understanding of the biomechanics of boxing and potentially contribute to improving training methods and enhancing athletes' performance.

The aim of this study was to gain knowledge on how effective mass affects the striking force of boxers. Therefore, the following research questions were formulated:

1. What values of effective mass and impulse of striking force and movement pattern did the studied boxers achieve?
2. What relationship does effective mass exhibit with striking force in the applied movement pattern?
3. How do obtained biomechanics and somatic variables affect effective mass?
4. Are there significant differences in values of effective mass between the lead jab and rear cross techniques?

The answers to these questions may contribute to expanding the current knowledge underlying the identification of biomechanical factors influencing the effective execution of hand strikes.

2. Materials and Methods

2.1. Participants

This study involved a group of 13 male boxers from various clubs located in Czeszochowa. This group had previously participated in other studies concerning the biomechanics of straight punches. The requirement for participating in the experiment was a minimum of 5 years of training experience or significant achievements in national-level sports. The athletes also had to declare optimal condition on the day of the study and absence of injuries. Their average body mass was 90.6 ± 19.2 kg, and their average height was 184.0 ± 7.4 cm. The participants' average training experience was 9.5 ± 6.5 years.

Among the 13 athletes, two were left-handed and utilized a reverse-stance attacking technique, which added diversity to the technical analysis. The mix of different boxers in the research group provided a good basis for carefully studying boxing techniques.

2.2. Ethics

The Human Subjects Research Committee of the Jan Długosz University scrutinized and approved the test protocol as meeting the criteria of Ethical Conduct for Research Involving Humans (KE-O/4/2022). All participants in the study were injury free, informed of the testing procedures, and voluntarily participated in the data collection.

2.3. Equipment

To assess impact force, a force plate served as the designated target. The force plate, an AMTI model MC12-2K from the 2000 series, was securely attached to a stable framework and shielded with a training barrier to protect participants from direct contact. The dimensions of the aluminum force plate were $305 \times 406 \times 79$ mm. The force plate was synchronized in time and space with Noraxon, Scottsdale, AZ, USA (MR 3.18). For capturing acceleration data, three wireless IMU sensors, specifically the Ultium EMG sensors manufactured by Noraxon, were utilized. These sensors are characterized by a sampling

rate of 2000 Hz and were engineered for acceleration measurements up to 4000 g. These sensors were affixed with Velcro straps and placed on the back of the hand, the upper forearm, and just below the shoulder on the arm (Figure 1).



Figure 1. Placement of IMU sensors on upper limb.

2.4. Protocol

Data collection was conducted at the Center for Human Movement Analysis, at the University facility. Participants were screened to ensure good health and lack of injuries. Following informed consent, participants completed a 10 min warm-up involving various exercises (e.g., jumps, swings, rotations, bends, and simulated boxing punches). They then practiced striking a force-plate-mounted target to familiarize themselves with the equipment and ensure proper target height.

Accelerometers were attached to the participant's nondominant upper limb (Figure 1). Participants stood facing the target and, upon instruction, performed 5 maximum-force strikes using the nondominant limb (lead hand jab). The break between hits was between 2 and 4 s, depending on the athlete's needs. Sensors were then moved to the dominant limb, and participants performed another 5 maximum-force strikes using their dominant limb (rear hand cross). The break time between strike series was regulated by the time of replacing sensors, allowing for rest.

The lead hand jab in boxing is a rapid, linear punch executed by the nondominant hand, and it primarily targets the opponent's cephalic region or torso. Biomechanically, the jab involves a swift extension of the shoulder, elbow, and wrist joints, translating to the fist as the endpoint. Power generation originates from a coordinated sequence of muscle activation and kinetic linking. This begins with the lower body, where ground reaction forces initiate a rotational movement of the hips and trunk. The core musculature provides stability, transferring energy up the kinetic chain through shoulder protraction, and ultimately into the punch [5].

The rear cross in boxing is a powerful, linear punch executed by the dominant hand and is often directed towards the opponent's cephalic region. Biomechanically, the rear cross exhibits a greater rotational component than a jab. It involves hip rotation, trunk

rotation, and shoulder protraction, with the elbow and wrist joints extending for impact. The kinetic chain generates greater power in the rear cross compared to the lead jab: ground reaction forces initiate the movement, transferring energy up through the legs, hips, and core. The rotational element maximizes power as the shoulder and arm act as the final levers delivering the forceful impact [11]. Figure 2 represents the equipment used to measure striking force: a strike pad and a force plate.



Figure 2. Force plate AMTI MC12-2K with a strike pad.

2.5. Data Processing and Data Analysis

We recorded five strikes for each boxing technique per participant. The measurement software (Noraxon MR 3.18 with Myomotion module) initially saved the data in Excel format (*.slk), which we then converted to *.xlsx for easier handling.

To find the maximum force of each strike, we used a Python script with the SciPy library's "findpeaks" function. We worked on this script collaboratively using the Deepnote platform. The script converted the raw data to m/s^2 and pinpointed the peaks.

For each set of five strikes, our script identified the events (the individual strikes) based on the maximum force value. It then measured the acceleration of each limb segment at that peak force moment. Each set of trials was broken down to show the five individual strikes (events), along with the duration, maximum impact force, and acceleration of each limb segment.

We decided that a strike began when the fist accelerated to 12 m/s^2 (slightly higher than Earth's gravity of 10 m/s^2 , as baseline of record is 1 g). We used the 12 m/s^2 threshold to be sure we were capturing the actual movement and to reduce errors, because the difference between 11 m/s^2 and 12 m/s^2 was insignificant (minimal shaking of hands affects detection of movement beginning). We also looked at the ground reaction force (GRF) to pinpoint the exact moment the fist hit the target, when the GRF value starts to increase. The strike ended when the GRF reached its maximum value. The script used is provided on the github platform (https://github.com/Dareczin/boxing_biomechanics, accessed on 1 March 2024). Data used in this analysis are fully available at <https://doi.org/>

[10.5281/zenodo.10729180](https://doi.org/10.5281/zenodo.10729180), accessed on 1 March 2024. After we created summary tables of all results, we computed the effective mass according to the following equation:

$$Me = \frac{F_{max}}{a} \quad (1)$$

where Me—effective mass, involved in a strike; Fmax—maximum force with which strike was performed; a—maximal acceleration at the moment of a contact with a target.

The implementation of the proximal-to-distal pattern was examined by analyzing the acceleration values generated by the upper arm, forearm, and fist during a punch. According to the concept, the fist, as the final segment, should strike the target with maximum speed resulting from the accumulation of energy from the preceding body segments. In the description of the results, they were recorded in a binary sequence, where “1” indicated the higher half of values and “0” indicated lower values. The first number corresponded to the fist, the second to the forearm, and the third to the upper arm. For example, 1-0-0 indicated that the acceleration value of the fist was higher than that of the forearm and the upper arm.

2.6. Statistical Analysis

After data analysis, the results were exported to Statistica 13 (TIBCO software, Palo Alto, CA, USA). Basic descriptive statistics were calculated, including means, standard deviations, medians, and ranges for various parameters such as total ground reaction force (GRF), fist acceleration (afist), forearm acceleration (aforearm), arm acceleration (aarm), target contact time, strike duration, and velocity of max force for both lead jab and rear cross punches. The Shapiro–Wilk test was conducted to assess the normality of the data distribution. Based on the results, the hypothesis of normal distribution was rejected for the variables “age”, “body mass”, “height”, “training tenure”, “total GRF”, “afist”, “aforearm”, and “aarm”.

Given the non-normal distribution of the data (Table 1), nonparametric tests were employed for further analysis. The Mann–Whitney U-test was applied to determine the significance of differences between lead jab and rear cross punches for various parameters. Statistical significance was set at $p < 0.05$. Spearman’s rank correlation coefficients were calculated to determine relationships between various variables, including effective mass, total GRF, fist acceleration, body mass, height, age, and training tenure.

Table 1. Mann–Whitney U-test (with continuity correction). The highlighted results are significant at $p < 0.05$.

Variable	Rank Sum Lead Jab	Rank Sum Rear Cross	U	Z	p	r (Effect Size)
total_GRF	2288.50	3927.50	518.50	−5.998	0.000	0.57
afist	2224.00	3992.00	454.00	−6.379	0.000	0.61
aforearm	2295.00	3921.00	525.00	−5.959	0.000	0.57
aarm	2917.00	3299.00	1147.00	−2.284	0.022	0.22
target contact time	2840.00	3376.00	1070.00	−2.739	0.006	0.26
strike duration	3583.00	2633.00	1255.00	1.645	0.099	0.16
velocity of max force	2413.00	3803.00	643.00	−5.262	0.000	0.50

To analyze the distribution of effective mass index across different punch patterns and body mass categories, descriptive statistics were computed for each subgroup, including means, standard deviations, medians, and interquartile ranges.

The implementation of the proximal-to-distal pattern was examined by analyzing the acceleration values generated by the upper arm, forearm, and fist during a punch. The patterns were recorded in a binary sequence where “1” indicated the higher half of values and “0” the lower half of values for each segment (fist–forearm–upper arm).

Graphical representations of the data, including box plots and correlation matrices, were created to visualize the relationships between variables and the distribution of effective mass across different categories and punch patterns.

In addition to the Mann–Whitney U-test, we calculated the G-score to assess the magnitude of the effect size for differences between lead jab and rear cross punches, particularly in terms of ground reaction force (GRF). The G-score revealed a moderate to large effect size. Furthermore, a sample size analysis was conducted to ensure that the study had sufficient power. With a sample size of 13 participants, the statistical power was calculated to exceed 80%, confirming that the study was adequately powered to detect significant differences between the two punch types.

3. Results

Table 1 displays the results of the Mann–Whitney U-test, comparing the lead jab and rear cross punches across various performance metrics. The analysis highlights significant differences between the two punches. The rear cross punch consistently outperformed the lead jab in key variables such as total ground reaction force (GRF), fist acceleration, and forearm acceleration, all of which showed highly significant differences ($p < 0.001$). For example, the effect size for GRF was 0.57, and for fist acceleration, it was 0.61, indicating large practical differences.

Moderate differences were also observed in arm acceleration (effect size = 0.22) and target contact time (effect size = 0.26), which were statistically significant ($p < 0.05$). These findings demonstrate that the rear cross punch achieved greater acceleration and stayed in contact with the target slightly longer than the lead jab. However, strike duration did not show a significant difference between the two punch types ($p = 0.099$, effect size = 0.16).

Clear differences between the lead jab and rear cross punches were observed in several measured variables, as shown in Table 2. The rear cross generated a significantly higher total ground reaction force (1709.277 ± 4866.206 N) compared to the lead jab (1182.552 ± 2508.125 N). Similarly, fist acceleration was greater in the rear cross (94.334 ± 184.594 m/s²) than in the lead jab (66.066 ± 195.109 m/s²). This pattern also held for the acceleration of the forearm and arm, with the rear cross showing higher values (67.110 ± 253.148 m/s² and 88.396 ± 191.780 m/s², respectively) than the lead jab (41.617 ± 110.235 m/s² and 81.360 ± 288.002 m/s², respectively).

Table 2. Descriptive statistics of registered variables.

Punch Type	Variable	Mean	Minimum	Maximum	Standard Deviation
lead jab n = 59	total_GRF (N)	1182.56	670.04	1748.19	250.81
	afist (m/s ²)	66.07	36.32	114.76	19.51
	aforearm (m/s ²)	41.62	22.46	65.32	11.02
	aarm (m/s ²)	81.36	28.57	206.47	28.80
	target contact time (s)	0.02	0.00	0.15	0.03
	strike duration (s)	0.18	0.07	0.20	0.04
	velocity of max force (m/s)	6.77	2.44	10.15	1.82
rear cross n = 52	total_GRF (N)	1709.28	1082.48	2866.76	486.62
	afist (m/s ²)	94.33	68.26	174.19	18.46
	aforearm (m/s ²)	67.11	34.33	146.74	25.31
	aarm (m/s ²)	88.40	47.69	123.48	19.18
	target contact time (s)	0.03	0.01	0.17	0.02
	strike duration (s)	0.17	0.08	0.20	0.03
	velocity of max force (m/s)	8.63	5.96	10.72	1.35

total_GRF—measurement of strike force, afist—acceleration a fist, forearm—acceleration of forearm, aarm—acceleration of arm.

The target contact time was slightly longer for the rear cross (0.030 ± 0.0244 s) compared to the lead jab (0.024 ± 0.0263 s). The duration of the strike was nearly the same for both punches, with the lead jab averaging 0.176 ± 0.0385 s and the rear cross aver-

aging 0.173 ± 0.0287 s. Finally, the velocity at maximum force was higher for the rear cross (8.628 ± 13.486 m/s) than for the lead jab (6.766 ± 18.177 m/s), indicating a more powerful impact.

Fist acceleration was also much higher in the rear cross punch ($U = 454.000$, $Z = -6.379$, $p < 0.001$), showing that the rear cross punch accelerates faster. The same trend was seen with forearm acceleration ($U = 525.000$, $Z = -5.960$, $p < 0.001$) and arm acceleration ($U = 1147.000$, $Z = -2.284$, $p = 0.022$), with both being higher in the rear cross punch.

The rear cross punch also had a longer contact time with the target ($U = 1070.000$, $Z = -2.739$, $p = 0.006$), meaning that it stayed in contact with the target slightly longer than the lead jab. However, the overall duration of the strikes was pretty much the same for both punches ($U = 1.255.000$, $Z = 1.646$, $p = 0.1$). Lastly, the speed at which the punch reached its maximum force was significantly higher for the rear cross ($U = 643.000$, $Z = -5.262$, $p < 0.001$), indicating a stronger impact.

The results showed clear differences between the lead jab and rear cross punches. The rear cross punch generated a much higher total ground reaction force compared to the lead jab, with very significant statistics ($U = 518.500$, $Z = -5.998$, $p < 0.001$). This means that the rear cross punch hits with a lot more force.

Based on the recorded data, the effective mass values were calculated for both the lead jab and the rear cross punches. Even though there were big differences in the total ground reaction force (GRF) and fist acceleration for these punches, the effective mass values were surprisingly similar. On average, the effective mass for all punches was $21.29\% \pm 4.95\%$ (18.75 kg ± 5.40 kg). Specifically, the lead jab had an average effective mass of $21.5\% \pm 5.07\%$, while the rear cross was $21.04\% \pm 4.83\%$. The lead jab's effective mass ranged from a minimum of 11.90% to a maximum of 38.32% , and for the rear cross, it ranged from 14.49% to 36.25% .

Figure 3 illustrates the effective mass values for lead jab and rear cross punches, presenting effective mass index and as a percentage (%) of total body mass. Based on the data from Table 3, the average effective mass index for lead jab punches was 18.95 ± 5.29 , which corresponds to $21.51\% \pm 5.07\%$ of the body mass. In comparison, the rear cross punches had an average effective mass index of 18.50 ± 5.56 , representing $21.04\% \pm 4.83\%$ of the body mass. For lead jab punches, the effective mass index values ranged from a minimum of 9.79 (11.90%) to a maximum of 31.81 (38.33%). The interquartile range for the lead jab ranged from 15.41 (18.03%) to 22.63 (23.70%), with a median value of 17.15 (20.46%). In the case of rear cross punches, the effective mass index values varied from 9.79 (14.49%) to 32.63 (36.25%).

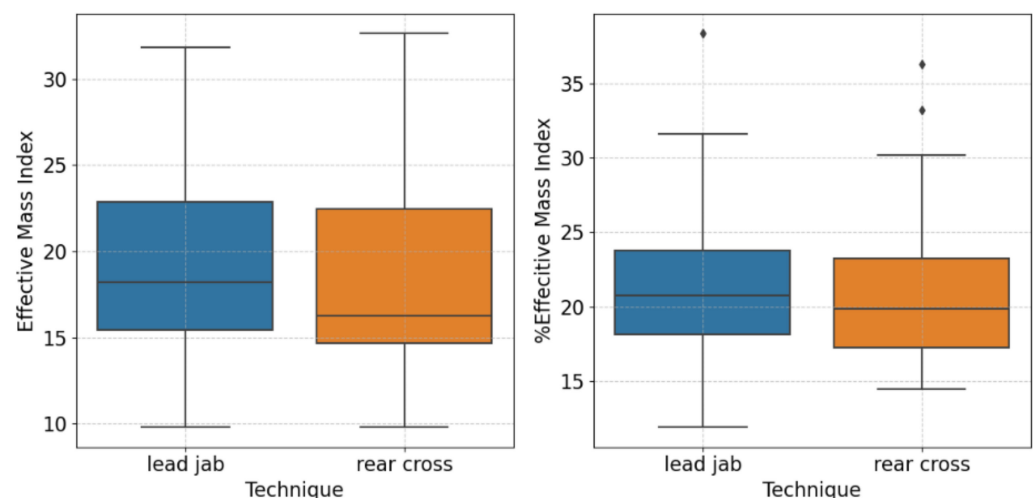


Figure 3. Effective mass index and % effective mass of lead jab and rear cross.

Figure 4 illustrates the relationship between total ground reaction force (GRF) and effective mass index (Me) divided into quartiles. The first quartile (Q1) of total GRF, with a

mean effective mass index of 11.95 ± 2.10 , ranged from 7.57 to 16.83. The second quartile (Q2) exhibited a mean effective mass index of 12.84 ± 4.11 , with values spanning from 6.70 to 28.67. The third quartile (Q3) showed a higher mean effective mass index of 15.86 ± 4.77 , ranging between 7.82 and 27.36. The fourth quartile (Q4), representing the highest GRF values, had a mean effective mass index of 16.58 ± 5.27 , with a minimum of 9.44 and a maximum of 27.51.

Table 3. Effective mass index divided into lead jab and rear cross.

Punch Type	Variable	Mean	Median	Minimum	Maximum	Lower Quartile	Upper Quartile	Standard Deviation
lead jab	Effective Mass Index	18.95	18.19	9.79	31.81	15.41	23.03	5.29
	%effective mass	21.51	20.73	11.90	38.33	18.04	23.97	5.08
rear cross	Effective Mass Index	18.50	16.27	9.79	32.63	14.68	22.50	5.56
	%effective mass	21.04	19.88	14.49	36.25	17.26	23.42	4.83

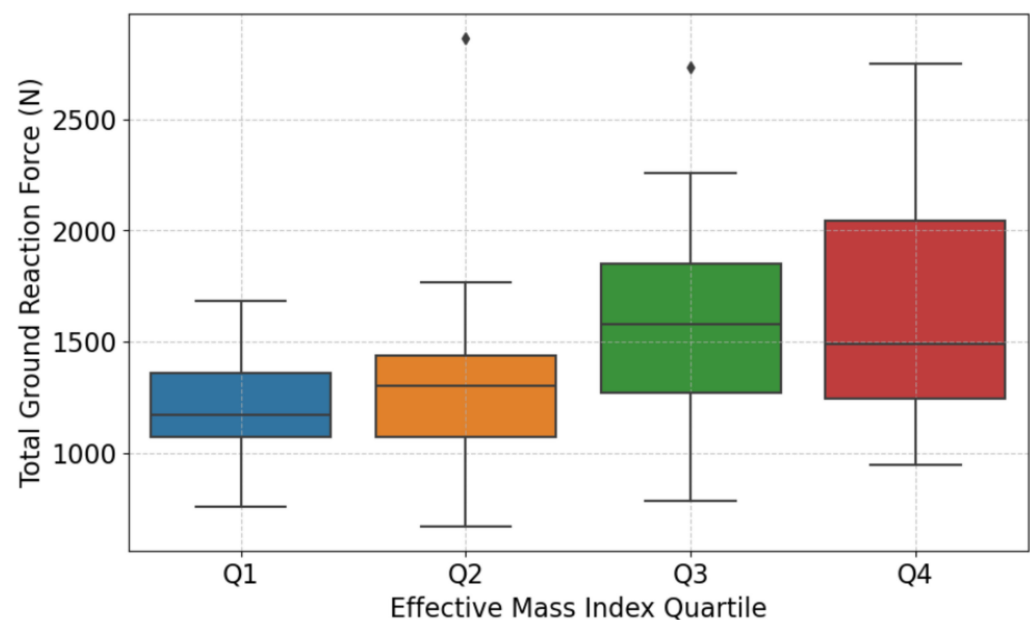


Figure 4. The relationship between total GRF and effective mass index in quartiles.

Figure 5 depicts the relationship between body mass and effective mass index (Me) across different body mass quartiles. The first quartile (Q1) of body mass, with a mean effective mass of 72.68 ± 12.56 kg, ranged from 58.0 kg to 98.0 kg. The second quartile (Q2) exhibited a mean effective mass of 88.61 ± 11.21 kg, with values spanning from 73.0 kg to 119.0 kg. The third quartile (Q3) had a mean effective mass of 88.26 ± 5.57 kg, ranging between 83.0 kg and 98.0 kg. The fourth quartile (Q4), representing the highest body mass values, showed a mean effective mass of 104.14 ± 22.96 kg, with a minimum of 83.0 kg and a maximum of 134.0 kg.

Figure 6 illustrates the relationship between body height and effective mass index (Me) divided into quartiles. The first quartile (Q1) of effective mass index, with a mean body height of 177.57 ± 6.56 cm, ranged from 170.0 cm to 190.0 cm. The second quartile (Q2) exhibited a mean body height of 184.29 ± 7.81 cm, with values spanning from 170.0 cm to 193.0 cm. The third quartile (Q3) showed a slightly higher mean body height of 186.00 ± 4.43 cm, ranging between 179.0 cm and 193.0 cm. The fourth quartile (Q4), representing the tallest participants, had a mean body height of 188.68 ± 6.74 cm, with a minimum of 179.0 cm and a maximum of 196.0 cm.

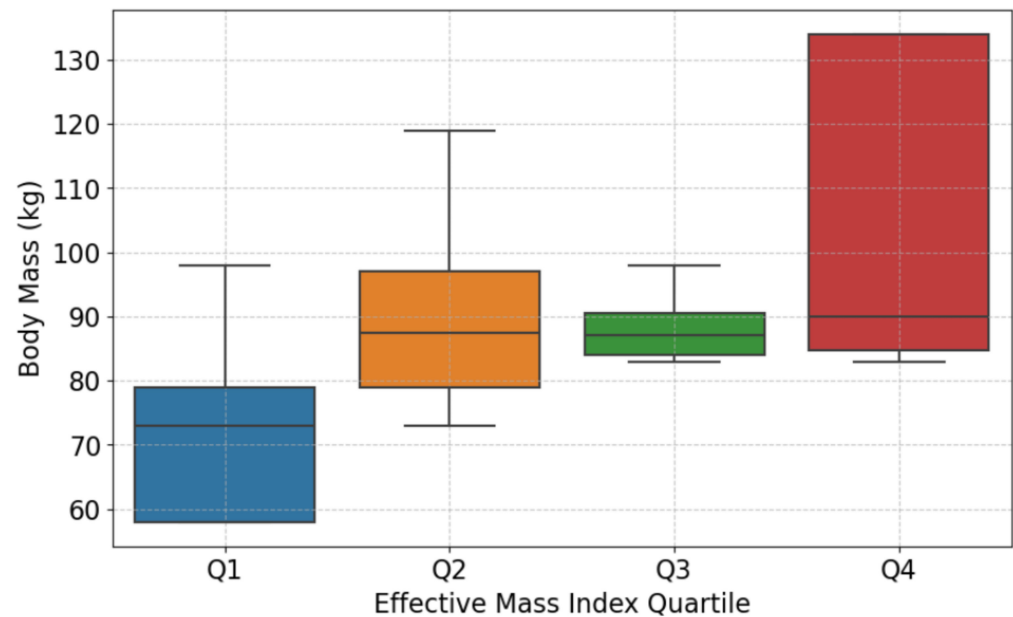


Figure 5. The relationship between body mass and effective mass index in quartiles.

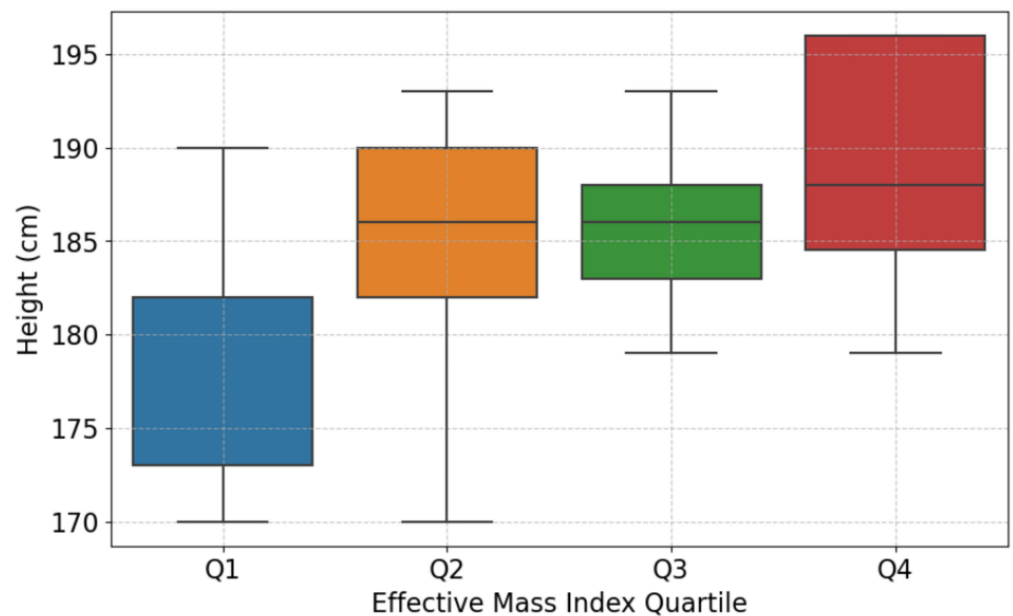


Figure 6. The relationship between body height and effective mass in quartiles.

Figure 7 illustrates the relationship between fist acceleration and effective mass index (Me) divided into quartiles. The first quartile (Q1) of effective mass index, with a mean fist acceleration of $94.37 \pm 18.37 \text{ m/s}^2$, ranged from 54.19 m/s^2 to 125.36 m/s^2 . The second quartile (Q2) exhibited a mean fist acceleration of $80.28 \pm 24.90 \text{ m/s}^2$, with values spanning from 43.30 m/s^2 to 174.19 m/s^2 . The third quartile (Q3) showed a slightly lower mean fist acceleration of $79.32 \pm 21.21 \text{ m/s}^2$, ranging between 42.98 m/s^2 and 121.01 m/s^2 . The fourth quartile (Q4), representing the highest fist acceleration values, had a mean fist acceleration of $63.26 \pm 19.62 \text{ m/s}^2$, with a minimum of 36.32 m/s^2 and a maximum of 112.00 m/s^2 .

Figure 8 illustrates the distribution of effective mass index (Me) values across different training tenure. The first quartile (Q1) of effective mass index, with a mean training tenure of 5.11 ± 3.62 years, ranged from 2.0 years to 16.0 years. The second quartile (Q2) exhibited a mean training tenure of 7.39 ± 5.19 years, with values spanning from 4.0 years to 22.0 years. The third quartile (Q3) had a mean training tenure of 10.44 ± 5.53 years, with

a range between 4.0 years and 22.0 years. The fourth quartile (Q4), representing the highest effective mass index, showed a mean training tenure of 10.57 ± 6.86 years, with a minimum of 4.0 years and a maximum of 22.0 years.

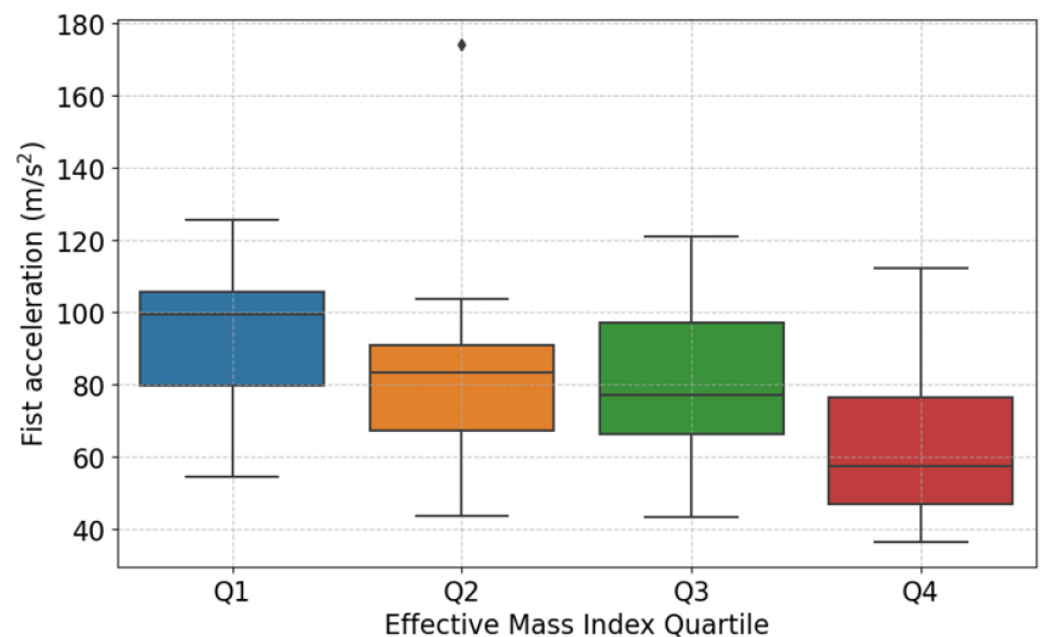


Figure 7. The relationship between fist acceleration and effective mass index in quartiles.

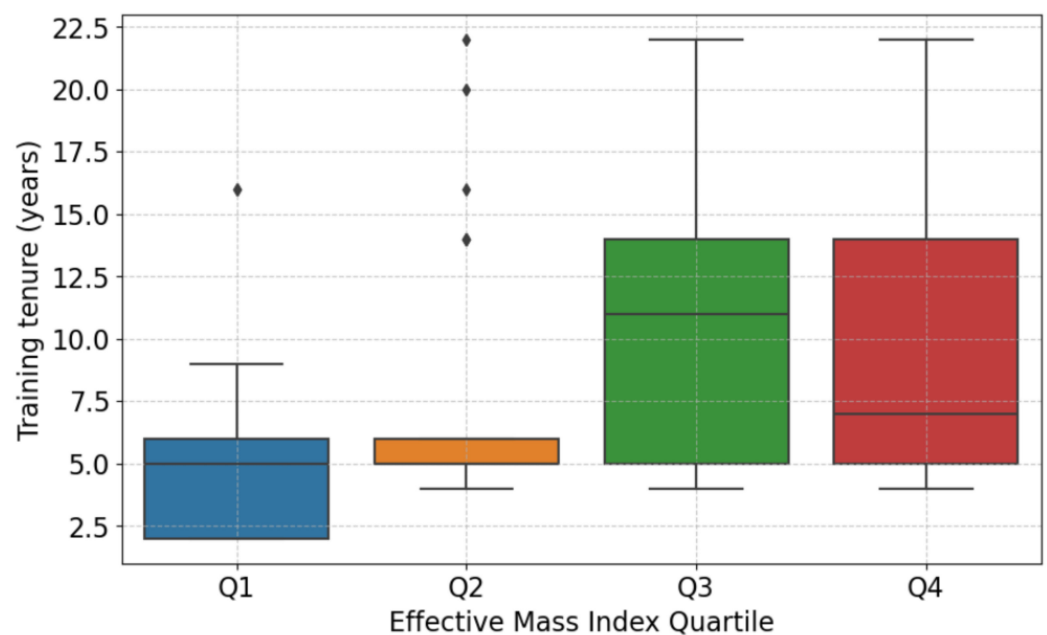


Figure 8. The relationship between training tenure and effective mass index in quartiles.

Figure 9 presents the Spearman correlation matrix for various variables related to the biomechanics of boxing punches, including the percentage of effective mass (% effective mass). The matrix highlights several prominent correlations. Training tenure shows a strong positive correlation with age ($\rho = 0.75$, statistically significant), and moderate positive correlations with body mass ($\rho = 0.35$) and effective mass index ($\rho = 0.35$), though these were not statistically significant.

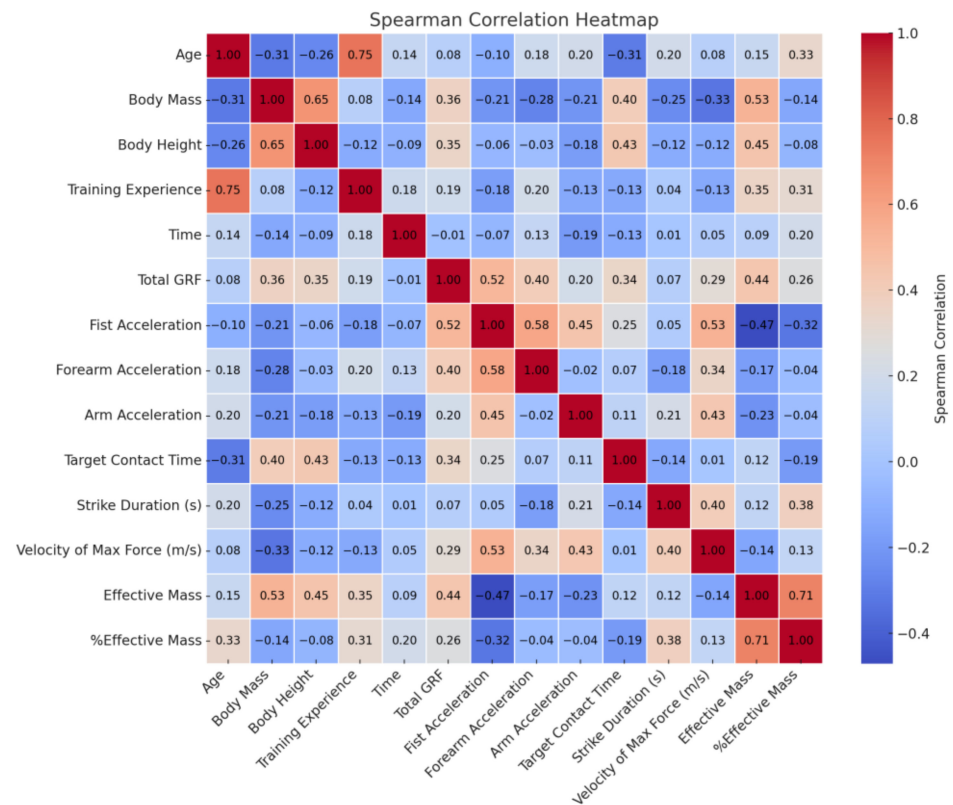


Figure 9. Spearman correlation matrix including all somatic and biomechanics variables.

Total ground reaction force (Total_GRF) exhibits a moderate positive correlation with fist acceleration (afist) ($\rho = 0.52$, statistically significant) and body mass ($\rho = 0.36$), though the latter was not statistically significant. Additionally, there is a weaker positive correlation with effective mass index ($\rho = 0.44$), but this was not statistically significant.

Effective mass index is strongly correlated with % effective mass ($\rho = 0.71$, statistically significant) and shows moderate positive correlations with body mass ($\rho = 0.45$, statistically significant) and training tenure ($\rho = 0.35$), though the latter was not statistically significant. Effective mass index also displays a moderate negative correlation with fist acceleration (afist) ($\rho = -0.47$, statistically significant).

The % effective mass is positively correlated with effective mass index ($\rho = 0.71$, statistically significant) and body mass ($\rho = 0.53$, statistically significant), and shows a moderate negative correlation with fist acceleration (afist) ($\rho = -0.32$), though this was not statistically significant. Body mass is positively correlated with height ($\rho = 0.65$, statistically significant), training tenure ($\rho = 0.35$), total GRF ($\rho = 0.36$), Effective mass index ($\rho = 0.45$, statistically significant), and % effective mass ($\rho = 0.53$, statistically significant). Age is strongly correlated with training tenure ($\rho = 0.75$, statistically significant), but exhibits weaker correlations with effective mass index ($\rho = 0.15$) and % effective mass ($\rho = 0.33$), neither of which were statistically significant.

Figure 10 presents the distribution of effective mass index values for different punch patterns. The punch patterns are denoted by a combination of three binary indicators (e.g., 0-0-0, 0-1-0), where each indicator represents a specific limb segment: fist–forearm–upper arm. The pattern 0-0-0, with 22 instances, has a mean effective mass index of 21.86 and a standard deviation of 4.71. The effective mass index for this pattern ranges from a minimum of 15.48 to a maximum of 30.62, with the interquartile range spanning from 18.29 to 24.80, and a median value of 22.10. For the pattern 0-0-1, which occurred 8 times, the mean effective mass index is significantly lower at 13.73, with a standard deviation of 2.54. The values range from 9.79 to 16.21, with the 25th and 75th percentiles at 11.62 and 15.41, respectively, and a median of 14.96. The 0-1-0 pattern, seen in 13 instances, shows a mean

effective mass index of 20.56 and a standard deviation of 5.42. The effective mass index ranges from 12.56 to 30.21, with the interquartile range from 15.35 to 23.35, and a median of 22.48. For the pattern 0-1-1, which has 12 occurrences, the mean effective mass index is 18.30 with a standard deviation of 5.11. The range is from 10.20 to 30.15, with the 25th and 75th percentiles at 15.53 and 20.62, respectively, and a median of 17.28 kg. The 1-0-0 pattern, observed 15 times, has a mean effective mass index of 19.18 and a standard deviation of 5.18. The values range from 13.96 to 31.81, with the interquartile range from 16.02 to 22.68, and a median of 17.07. For the pattern 1-0-1, occurring in 10 instances, the mean effective mass index is 15.82 with a standard deviation of 2.41. The effective mass index ranges from 10.83 to 19.47, with the 25th and 75th percentiles at 14.66 and 16.94, respectively, and a median of 15.95. The 1-1-0 pattern, with 5 instances, shows the highest mean effective mass index of 24.17 and a standard deviation of 7.42. The effective mass index for this pattern ranges from 14.79 to 32.63, with the interquartile range from 18.86 to 29.88, and a median of 24.70. Lastly, the 1-1-1 pattern, seen in 26 instances, has a mean effective mass index of 16.74 with a standard deviation of 4.93. The values range from 9.79 to 26.27, with the 25th and 75th percentiles at 12.72 and 21.03, respectively, and a median of 14.90. Overall, Figure 10 highlights the variability in effective mass index across different punch patterns, indicating distinct biomechanical characteristics associated with each pattern. The patterns with the highest effective mass index (1-1-0 and 0-0-0) suggest more efficient mass utilization in generating fist acceleration, while those with lower effective mass index (0-0-1 and 1-0-1) indicate less effective use of body mass in the strikes.

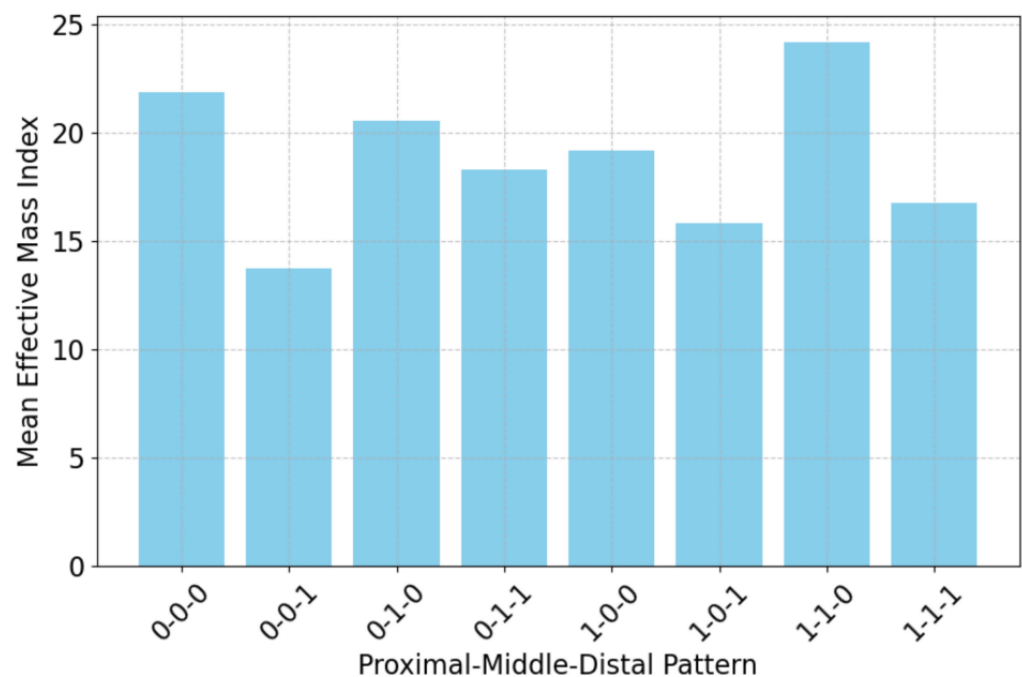


Figure 10. Distribution of effective mass index values for different punch patterns.

Figure 11 presents the distribution of effective mass index values across different body mass categories (low, medium, high, very high) based on the acceleration. For the low body mass category, the effective mass index values vary among the punch acceleration patterns. The 0-0-0 pattern shows an effective mass of 16.17, while the 0-0-1 pattern has a significantly lower effective mass index of 10.81. The 0-1-0 and 0-1-1 patterns have effective mass indexes of 13.81 and 10.20, respectively. Patterns 1-0-0 and 1-0-1 display effective mass indexes of 15.73 and 14.47, respectively, whereas the 1-1-0 and 1-1-1 patterns show values of 14.79 and 12.63, respectively. In the medium body mass category, the effective mass index values are generally higher. The 0-0-0 pattern shows an effective mass index of 20.62, while the 0-0-1 pattern has a lower value of 14.97. The 0-1-0 pattern displays a

notably high effective mass index of 22.91, and the 0-1-1 pattern has a value of 16.39. The 1-0-0 pattern shows the highest effective mass index in this category at 23.38, whereas the 1-0-1 pattern has an effective mass index of 18.57. There are no data available for the 1-1-0 pattern, and the 1-1-1 pattern shows an effective mass index of 19.93. For the high body mass category, the 0-0-0 pattern exhibits an effective mass index of 22.96, and the 0-0-1 pattern shows a value of 16.18. The 0-1-0 pattern has an effective mass index of 19.54, while the 0-1-1 pattern shows a higher value of 20.70. The 1-0-0 pattern displays an effective mass of 20.26, and the 1-0-1 pattern has a lower value of 15.03. The 1-1-0 pattern has the highest effective mass index in this category at 26.52 kg, while the 1-1-1 pattern shows a value of 19.60 kg. In the very high body mass category, the data are more limited. The 0-0-0 pattern has an effective mass index of 22.44, and the 0-0-1 pattern shows a value of 15.06. The 0-1-0 pattern has the highest effective mass index in this category at 25.10, while the 0-1-1 pattern shows a value of 23.21. There are no data available for the 1-0-0 and 1-1-0 patterns in this category. The 1-0-1 pattern has an effective mass index of 17.79, and there are no data available for the 1-1-1 pattern. Overall, Figure 11 demonstrates the variability in effective mass index across different body mass categories and punch acceleration patterns. Higher body mass categories generally exhibit higher effective mass index values, indicating that greater body mass contributes to more effective utilization of mass in generating punch force. However, there are exceptions and variations within each category, reflecting the complexity of biomechanics in boxing.

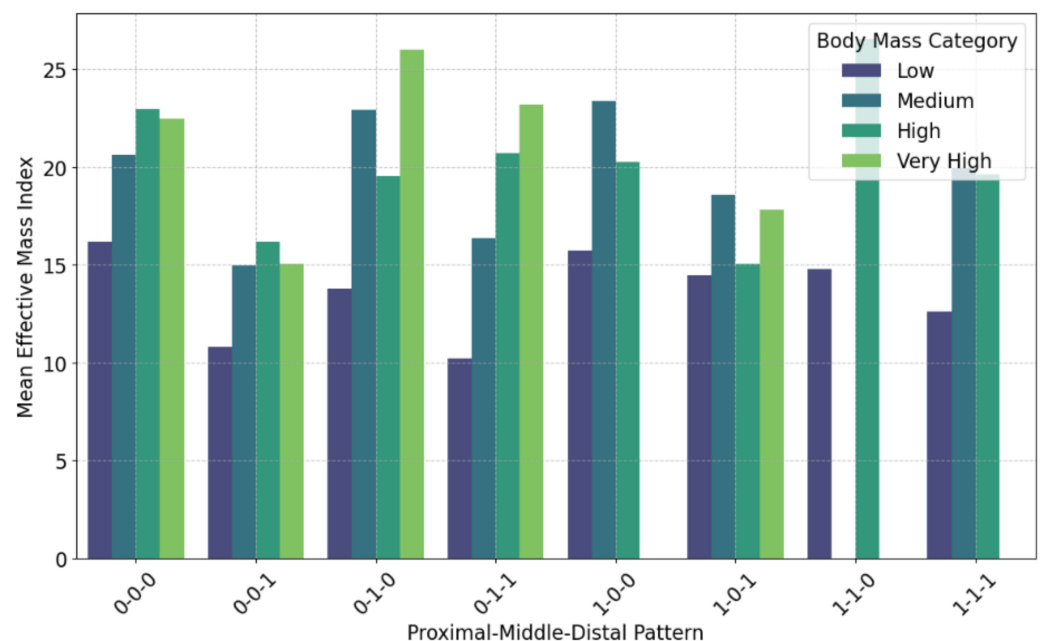


Figure 11. Distribution of effective mass index values for different body mass categories.

4. Discussion

The following work is an extension of previous research on the differences in punch force and fist acceleration between the lead jab and the rear cross. The primary objective of this study was to elucidate the relationship between effective mass, striking force, and fist acceleration in lead jab and rear cross boxing punches, while also considering other factors. The study revealed key findings that show significant differences in generated force and acceleration between these two types of punches; however, the effective mass of these punches is very similar. Additionally, the study identified several key factors that correlate with effective mass, including body mass and training tenure. These correlations highlight the complex biomechanics involved in executing boxing punches. The interplay of these variables underscores the multifaceted nature of force generation in boxing.

The results revealed that despite significant differences in total GRF and fist acceleration, rear cross punches exhibit very similar effective mass values compared to lead jabs. The mean effective mass for rear cross punches was slightly lower at 18.50 ± 5.56 kg (21.04% of body mass) compared to 18.95 ± 5.29 kg (21.51% of body mass) for lead jabs. However, the significantly greater fist acceleration mitigated this difference—although the rear cross is faster and stronger than the lead jab, the utilization of body mass is very similar. The slight difference in effective mass index in favor of the rear cross may be due to the fact that rear cross punches are delivered with the dominant hand and involve more body rotation, thereby utilizing slightly more body mass to generate force, as was suggested in studies before [12].

An untypical relationship with a weakening of the trend between total GRF and effective mass was observed, as illustrated in Figure 4. The data showed that higher total GRF values corresponded to increased effective mass across the quartiles. For example, in the fourth quartile, the mean effective mass index was 16.58 ± 5.27 , compared to 11.95 ± 2.10 in the first quartile. This relationship indicates that boxers who generate higher ground reaction forces can better transfer their body mass into their punches, enhancing punch force, which corresponds to other research in this discipline [2]. Interestingly, the average effective mass index in the fourth quartile is slightly lower than in the third quartile. It can be hypothesized that while higher total GRF impacts increased effective mass, there might be a certain level of total GRF where further increases are no longer beneficial for effective mass. To confirm this hypothesis, further studies with a larger and more diverse sample group in terms of body mass would be needed.

Figure 5 demonstrated a similar trend, where higher body mass was associated with higher effective mass. Boxers in the highest effective mass index quartile (Q4) had a mean body mass of 104.14 ± 22.96 , compared to 72.68 ± 12.56 in the lowest quartile (Q1). This suggests that heavier boxers have a greater capacity to use their body weight effectively in generating punch force, which could be advantageous in delivering more powerful punches. However, once again, the difference between the average values in Q3 and Q4 is very small. This raises the question of whether there is a certain body mass value beyond which it no longer positively affects the effective mass index in punches. To definitively answer this question, further research on larger groups is needed.

The correlation between body height and effective mass, as shown in Figure 6, was less pronounced compared to body mass. While there was a general trend of increasing effective mass with height, the correlation was weaker. For example, the mean body height in the tallest quartile (Q4) was 188.68 ± 6.74 cm, compared to 177.57 ± 6.56 cm in the shortest quartile (Q1). The mean values in the second, third, and fourth quartiles (Q1, Q2, and Q3) were nearly identical. This suggests that body height does not play a significant role in determining effective mass, especially in the context of the work of other researchers, who demonstrated greater impact power generation capabilities in athletes with longer body segments, and, therefore, also greater body height [13]. Examining a larger group of athletes with diverse body heights but similar body mass would be an interesting extension of the study.

An inverse relationship between fist acceleration and effective mass was observed, as detailed in Figure 7. Higher acceleration values corresponded to lower effective mass, as directly indicated by the equation underlying the calculations in this study. For instance, in the fourth quartile of effective mass index, the mean fist acceleration was 63.26 ± 19.62 m/s², compared to 94.37 ± 18.37 m/s² in the first quartile. This can be interpreted as reflecting a trade-off between speed and force—while higher acceleration may increase punch speed, it does not necessarily translate to higher effective mass, which was also observed in studies conducted on athletes in the past [4].

Figure 8 demonstrates a positive correlation between training tenure and effective mass. Boxers with longer training experience tend to have higher effective mass values. For example, the mean training tenure in the fourth quartile of effective mass was 10.57 ± 6.86 years, compared to 5.11 ± 3.62 years in the first quartile. It can be concluded

that with training experience, the athlete's motor skills and technical abilities also increase. Experienced boxers likely have developed better techniques for maximizing their effective mass, resulting in more powerful punches. Years of training enable boxers to naturally utilize their body mass. This is confirmed by the work of other researchers, where it has been shown that fighters with longer training experience have the ability to generate greater striking force [1,13,14].

In interpreting the results of implementing the proximal-to-distal pattern, the following key was adopted: 1. Ideal pattern (1-1-1)—indicates effective energy transfer through the body segments and indicates proper execution of the punch consistent with the proximal-to-distal pattern; 2. Suboptimal patterns (e.g., 0-1-0, 0-0-1)—indicate issues with energy transfer through the body segments; analysis of punching technique and potential training corrections are necessary. The analysis of different punch patterns, as shown in Figure 10, revealed variability in effective mass. Patterns such as 1-1-0 (mean effective mass 24.17) and 0-0-0 (21.86) exhibited higher effective mass values, indicating more efficient utilization of body mass. In contrast, patterns such as 0-0-1 (13.73) and 1-0-1 (15.82) had lower effective mass values. This suggests that punches adhering to the concept of the proximal-to-distal pattern, as well as those that did not perfectly fit it but also did not represent its inverse, are more effective in utilizing body mass to generate force, potentially due to differences in technique and body mechanics. In such cases, energy was effectively transferred through the body segments, resulting in maximum fist speed. In the discussion with Bernstein's seminal works on the proximal-to-distal pattern, which suggest the 1-1-1 pattern as the most desirable, it turns out that patterns such as 1-1-0 can still optimize energy transfer. Specifically, the shoulder rigidity (lower shoulder acceleration) in the 1-1-0 pattern allows for effective energy transmission from the torso to the fist while maintaining high fist acceleration. Incorporating the 1-1-1 pattern into teaching processes emphasizes optimal movement mechanics, while also highlighting patterns like 0-0-0 as effective alternatives in movement training. In studies of motor control, Bernstein's approach underscores the importance of understanding how movement patterns influence energy transfer and the overall effectiveness of sports techniques. Patterns resembling 1-1-0 demonstrate subtle adaptations that balance biomechanical efficiency with practical application, offering valuable insights for training methodologies [15,16]. It is also worth noting that the proximal-to-distal pattern is most desired in throwing-type striking and kicking techniques, while straight punches can be classified as techniques that are half throwing and half pushing, which can result in ambiguous execution technique for these strikes by athletes [17].

Figure 11 highlights the distribution of effective mass across different body mass categories and punch patterns. Higher body mass categories generally showed higher effective mass values, such as the 0-0-0 pattern in the very high body mass category (22.44 kg) compared to the low body mass category (16.17 kg). However, there were variations within each category, indicating that while body mass contributes to effective mass, individual technique and punch patterns also play critical roles.

The Spearman correlation matrix (Figure 9) provides further insights into the relationships between various variables and effective mass. From the research methodology itself, there is a strong correlation between the effective mass index and % effective mass ($r = 0.71$). However, key correlations also include the positive relationship between body mass and effective mass ($\rho = 0.45$). Additionally, training tenure showed positive correlations with both effective mass ($\rho = 0.35$) and % effective mass ($r = 0.31$), highlighting the importance of experience in optimizing punch force. The inverse correlation between fist acceleration and effective mass ($r = -0.47$) underscores the trade-off between speed and mass utilization in punch dynamics, also directly resulting from the research methodology, as described earlier.

These findings have practical implications for boxer training. Focusing on techniques that improve effective utilization of body mass can increase punch force. Years of training improve the athlete's technical skills, so the training should be focused on the right aspects. The more a boxer strikes, the more they become attuned to the nuances of delivering

a powerful punch. This process involves an ongoing cycle of receiving and interpreting feedback from both their opponent's reactions and their own bodily sensations. For instance, the immediate impact on the opponent can indicate the force and effectiveness of the punch, while the boxer's own physical responses (such as the feeling in their muscles and the alignment of their body) provide critical insights into their technique. This concept is intrinsically linked to Newton's second law of motion, which states that force equals mass times acceleration. In practice, each punch a boxer throws acts as a real-time experiment, offering biofeedback that helps them optimize their technique. Moreover, the theory of embodied cognition suggests that this type of biofeedback is crucial. It emphasizes that cognitive processes are deeply rooted in the body's interactions with the environment, thus highlighting the importance of physical feedback in refining punching technique and enhancing overall performance [18]. Training programs should concentrate on optimizing punching technique, especially in terms of proximal–distal pattern execution—particular attention should be paid to dynamic training. Athletes should also consider optimizing their body mass, as the effectiveness of techniques does not increase directly proportionally with body mass. Additionally, incorporating strength and conditioning exercises to improve muscle coordination and stability can further benefit total ground reaction force (total GRF), and, consequently, punch effectiveness, as was suggested in other studies—it is recommended to use specific strength training for the lower limbs and techniques that stimulate neuronal adaptations, such as box jumps and bench press, to improve the ability to generate the strength and power required for boxing techniques, utilizing the potential of preactivation before punch execution [19,20].

While the study provides valuable insights, it is important to consider its limitations. Primarily, the sample size was relatively small, and the study only included male boxers from a specific region. Including women in the sample would allow for examining differences in effective utilization of body mass during punches between both genders. Although the participants trained in various sports clubs, additional regional diversity would provide more data on training methods. In future research, a larger and more diverse sample should be considered to confirm these results. It should also be noted that the index itself has a complex relationship and may need to be modified in the future. Additionally, expanding the research methodology to include hooks and uppercuts would provide more information on the potential for punch force generation and fist acceleration and could be compared to results of other studies [5,21]. Furthermore, investigating the role of muscle strength, coordination, and different training methods could provide a more comprehensive understanding of the factors influencing effective mass and punch force. It should also be noted that the study did not take into account the injury histories of the athletes, and injuries are very common in boxing. However, it is worth mentioning that boxers usually recover from injuries faster than athletes in other combat sports [22]. Even though the athletes declared full fitness and no injuries, their injury history may affect their ability to deliver powerful punches.

In conclusion, this study emphasizes the crucial role of effective mass in the biomechanics of boxing punches. Factors such as body mass, training experience, and ground reaction force significantly influence effective mass and, consequently, punch force. These findings can serve as guidelines for training practitioners aiming to improve punch effectiveness and overall performance in boxing. They can be useful for coaches and athletes striving for better results in boxing. Improving punch efficiency through proper technique, optimizing body mass utilization, and increasing ground reaction force can contribute to success in the ring.

5. Conclusions

This study highlights the crucial role of effective mass in boxing punch biomechanics, revealing several key findings. Despite significant differences in total ground reaction force between rear cross (1709.28 ± 486.62 N) and lead jab (1182.56 ± 250.81 N) punches, their effective mass values were similar (rear cross: 18.50 ± 5.56 kg, 21.04% of body mass; lead

jab: 18.95 ± 5.29 kg, 21.51% of body mass). This suggests that both punches efficiently utilize body mass, with the rear cross generating more force through higher acceleration.

Higher body mass correlated with increased effective mass, indicating that heavier boxers can transfer more body weight into their punches, although this relationship was not directly proportional. Training experience positively influenced effective mass, highlighting the importance of long-term skill development. An inverse relationship between fist acceleration and effective mass was observed, indicating a trade-off between punch speed and mass utilization. Certain punch patterns, particularly 1-1-0 and 0-0-0, exhibited higher effective mass values, suggesting more efficient body mass utilization.

These findings have significant implications for boxing training and performance optimization. Future research should explore these relationships across a more diverse sample, including female boxers and various weight categories, to further elucidate the complex biomechanics of boxing punches.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The raw data and code presented in this study are openly available in Zenodo at <https://doi.org/10.5281/zenodo.10729180>, reference number [12].

Conflicts of Interest: The authors declare no conflicts of interest.

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