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Higher Values of Force and Acceleration in Rear Cross Than Lead Jab: Differences in Technique Execution by Boxers

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Abstract: Background: Boxing, a globally popular combat sport, demands technical precision and powerful strikes at the same time. The kinetic assessment of straight punches, specifically the rear cross and lead jab, is crucial for understanding the biomechanical factors influencing punch effectiveness. This study aims to explore the kinetic properties of these punches in trained boxers, focusing on punch force, acceleration, and the concept of a proximal-to-distal pattern. Methods: Thirteen advanced-level male boxers (body weight 90.6 ± 19.2 kg, height 184.0 ± 7.4 cm, experience 9.5 ± 6.5 y) from local clubs participated in this study. Using a force plate and wireless IMU sensors, we recorded punch force and limb acceleration during the execution of rear-cross and lead-jab punches. Data analysis involved statistical tests to compare the kinetic differences (Mann–Whitney U-test) between the two punch types and assessment of the influence of body mass and training tenure on punch effectiveness (multiple regression analysis). Significant differences were observed between the rear cross and lead jab in terms of total ground reaction force ($\bar{x}$ = 1709.28 N vs. $\bar{x}$ = 1176.55 N), acceleration of the fist ($\bar{x}$ = 94.33 m/s^2 vs. $\bar{x}$ = 66.07 m/s^2), forearm ($\bar{x}$ = 67.11 m/s^2 vs. $\bar{x}$ = 41.62 m/s^2) and arm ($\bar{x}$ = 88.40 m/s^2 vs. $\bar{x}$ = 81.36 m/s^2), and target contact time ($\bar{x}$ = 0.03 s vs. 0.02 s). The rear-cross punch exhibited higher kinetic values, indicating greater effectiveness. Additionally, body mass and training tenure were identified as significant factors influencing punch force (R^2 score = 0.640). Conclusions: This study confirmed the biomechanical superiority of the rear cross over the lead jab in terms of generated force among trained boxers. The findings highlight the importance of coordination between each segment's acceleration to generate a powerful strike. These insights are valuable for coaches and athletes in optimizing training strategies for boxing.

Keywords: boxing; kinetic analysis; punch force; accelerometry; biomechanics

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1. Introduction

Boxing is one of the most popular forms of combat sport in the world. It evolved from simple fist fights to become a professional sport with specific rules and systematized training methods. Boxers wear special protective gloves and, in some forms, headgear. The fight takes place in a designated ring, over a specified number of rounds with breaks in between. Participants are allotted a specific time for each round, during which they strive to score points through precise strikes to designated areas of the opponent's body [1]. While the rules of this sport have evolved over the years, boxing itself consistently captivates and attracts. It appeals not only to practitioners but also to sports scientists seeking to thoroughly understand the mechanisms behind human movements in powerful strikes. Combat sports require athletes not only to deliver destructive blows but also to possess endurance and tactical skills to be able to endure many rounds of intensive fighting with opponents. Endurance requirements, and being able to deliver strong punches over a long period of time, require a superb striking technique [2]. This is one of the reasons why sports biomechanics are interesting in the investigation of properties characterizing specific techniques [3,4].

Depending on the type of punch thrown (cross, hook, uppercut), differences in its power can be observed [5]. Furthermore, the quality of the strike depends on the mass of the athlete [6] and the level of his technical training [7]. The development of technology allows for advanced biomechanical measurements, such as the analysis of forces and movements occurring during the strikes. Load cells and force platforms, as well as sophisticated motion measurement systems, consisting of accelerometer arrays, are used for this purpose [3,8]. Research on the biomechanics of boxing often relies on advanced force platforms, enabling precise measurement of various motion parameters and forces acting on a boxer's body. This tool facilitates a better understanding of motion mechanics, leading to the refinement of techniques and training methods. Accelerometers (inertial measurement units—IMU), used in biomechanical studies, allow scientists to precisely measure accelerations and changes in velocity, becoming crucial in motion analysis [9]. Most studies in martial arts biomechanics use combinations of force plates and motion analysis systems, depending on whether there is a stereophotogrammetric method with cameras or IMU units. Both devices are put in sync to minimize measurement errors, allowing the capture of all variables at specific times [10].

One of the main areas of interest is strike force as one of the performance indicators of athletes. The second one is velocity or acceleration at its peak, which is also perceived as one of the benchmarks of athletic abilities [11]. Scientists try to quantify and understand the effect of a strike's power based on classical physics principles, where force is related to mass and acceleration. Successful utilization of one's mass with its proper acceleration is considered a key to maximization of athlete capabilities—this is given the name, effective mass [6].

In studies focusing on combat sports athletes, the presence of a proximal–distal pattern has been observed. The proximal–distal pattern refers to sequential increases in speed as one moves away from the body's center. Body segments closer to the core (proximal) attain lower speeds than those further from the core (distal). As a result, the proximal–distal pattern is observed in many fighting techniques, where speed and force are transferred from areas closer to the torso to areas further away from it, aiding in the efficient utilization of the entire body during technique execution [12]. The proximal-to-distal pattern occurs during throw-like movements, when particular segments behave like a whip. Proximal segments achieve their maximal velocity faster and with lower values than more distal parts [13]. This sequence is considered to be most efficient in terms of delivering the strongest blows in these types of strikes. Moreover, some authors point out that there is a double-peak activation pattern, supporting a view that not only initial torque but also the final stiffening of body parts and their acceleration matters [14]. The phenomena of particular segment kinematics and its dependence on the final result of a strike have not yet been fully explored, leaving space to conduct more research on some forms of martial arts.

Combat sports, especially boxing, have always captured attention due to the quality of technique and precision in executing specific movements. This study specifically focuses on one of the fundamental techniques of this discipline—the straight punch, with particular attention to the difference between a straight punch delivered with the lead hand (jab) and one delivered with the rear hand (cross), which proves to differ significantly in terms of the achieved values [15].

In the context of this field, the present study is dedicated to the kinetic assessment of straight punches in boxing, taking into consideration the significant factor of initial stance and body rotation. The aim of this study was to assess the recorded values of punch force, contact time, acceleration, and determination of effective mass during straight punches in boxers. Consequently, the following research questions were formulated:

1. What are the values of the strike force and acceleration techniques delivered by the examined boxers?
2. Are there kinematic differences between the straight punch techniques—rear cross and lead jab?

3. Do lead-jab and rear-cross punches thrown by boxers exhibit a proximal-to-distal pattern in terms of limb velocity?

We hypothesize that the lead jab, being a faster strike, will generate higher acceleration values but lower force values. We also suspect that boxing straight punch techniques exhibit a proximal-to-distal pattern similar to other striking techniques in combat sports.

The answers to these questions can shed light on the biomechanics of effective punches in boxing. This new knowledge will not only improve our understanding of movement in this sport but also contribute to the development of more effective training methods and the identification of what truly makes a punch powerful.

2. Materials and Methods

2.1. Participants

The research group consisted of 13 male boxers (body weight 90.6 ± 19.2 kg, height 184.0 ± 7.4 cm, experience 9.5 ± 6.5 y) from different local boxing gyms in Częstochowa, demonstrating advanced skills and technical training. To qualify for participation in the study, athletes were required to have a minimum of five years of training experience or significant sports achievements, such as medals at regional, national, or a professional boxing career. Additionally, participants had to be actively training at the time of the study and reported no injuries.

It is emphasized that all examined boxers were injury-free on the day of the study, confirming their ability to participate in experiments safely. Furthermore, all participants declared optimal physical fitness, which was crucial for the reliability of the results. Among the 13 athletes, two were left-handed and employed a reverse-stance attacking technique, adding an extra dimension of diversity to the technical analysis. Such a composition of the research group provides a solid foundation for conducting a precise analysis of boxing techniques.

2.2. Ethics

The Human Subjects Research Committee of the Jan Dlugosz 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 informed of the testing procedures and voluntarily participated in the data collection.

2.3. Equipment

To measure the impact force, a force plate positioned as the target was utilized. The force plate, an AMTI model MC12-2K from the 2000 series (AMTI, Watertown, MA, USA), was affixed to a stable structure and covered with a training shield to safeguard participants from direct contact. The dimensions of the aluminum force plate were 305 × 406 × 79 mm. Its maximum force capacity was 4450 N for both F_x and F_y, and 8900 N for F_z. The force plate was synchronized in both time and space with Noraxon (MR 3.18, Scottsdale, AZ, USA). To capture acceleration data, there were employed 3 wireless IMU sensors, specifically the Ultium model by Noraxon, synchronized with the force plate. The IMU sensors had a sampling rate of 2000 Hz and were designed for acceleration measurements up to 4000 g. These sensors were strategically placed with Velcro straps tape on the back of the hand, the upper forearm, and on the arm just below the shoulder (refer to Figure 1).

Figure 1. IMU sensors placement and attachment to the upper limb.

2.4. Protocol

Data were collected at the Center for Human Movement Analysis, Jan Dlugosz University of Humanities and Sciences, Częstochowa. Participants, after declaring their optimal training form and confirming their healthy state, performed a 10 min warm-up comprising jumping exercises, swings, joint rotations, torso bends, and also air punches using boxing techniques. Subsequently, they executed several trial strikes on a target mounted to a force plate to familiarize themselves with the device, its impact absorption capabilities, and the proper height adjustment of the target. Accelerometers were then attached to the non-dominant upper limb of the participants in accordance with Figure 1, and they positioned themselves in front of the target. Upon the examiner's command, the participants initiated a set of 5 strikes with the maximum possible force using the non-dominant limb (lead-hand jab) (Figures 2 and 3). After these 5 strikes, the sensors were removed and placed on the dominant upper limb, and the participants began another set of 5 strikes with the maximum possible force using the dominant limb (rear-hand cross).

Figure 2. Strike pad placed on a force plate AMTI MC12-2K.

Figure 3. Example of participant's lead jab and rear cross with the view for force plate with padding, imitating shield. All analyses were video-supported for additional feedback during computation of results.

2.5. Data Processing and Data Analysis

The process of data acquisition involved capturing five strikes for each technique per participant. Initially, the data were extracted from the measurement software (Noraxon MR 3.18 with Myomotion module) in the Excel *.slk format and later converted to *.xlsx format for improved processing. The Python script, utilizing the SciPy library and the findpeaks function, was employed to determine the maximum force. The code involved uploading data to the Deepnote platform, facilitating real-time collaboration on data projects. It encompassed the conversion of raw data to m/s^2 and peak detection. Given that data were collected for five strikes per file, the code identified events (strikes) around the maximum force value at a specific strike, subsequently pinpointing the acceleration values of each marker at the time of maximum force. Each trial was segmented into five strikes, and the code specified the duration of each strike, along with the maximum impact force and acceleration of individual limb segments. To select the data, it was assumed that the strike began when the fist reached an acceleration of 12 m/s^2. The accelerometers were correlated with the Earth's acceleration, assumed to be 10 m/s^2. The time difference in reaching values between 11 m/s^2 and 12 m/s^2 was marginal. Therefore, to eliminate measurement errors, the threshold for the beginning of the movement was set to 12 m/s^2. A specific moment of strike was identified when the fist initiated contact with the target, and the GRF (Ground Reaction Force) value began to rise. The end of the strike was defined as the moment of reaching the maximum value of GRF. The accelerations of the fist, forearm, and arm reached their highest values only after the completion of the strike, due to the rapid rebound of the limb after contact with the target. Code is available at the GitHub repository via link https://github.com/Dareczin/boxing_biomechanics (accessed on 22 February 2024). All the variables' code names used in this study are the same as those used in the provided code and left on purpose for transparency and reproducibility standards. Graphical representation of a single strike and the way of defining variables are presented in Figure 4.

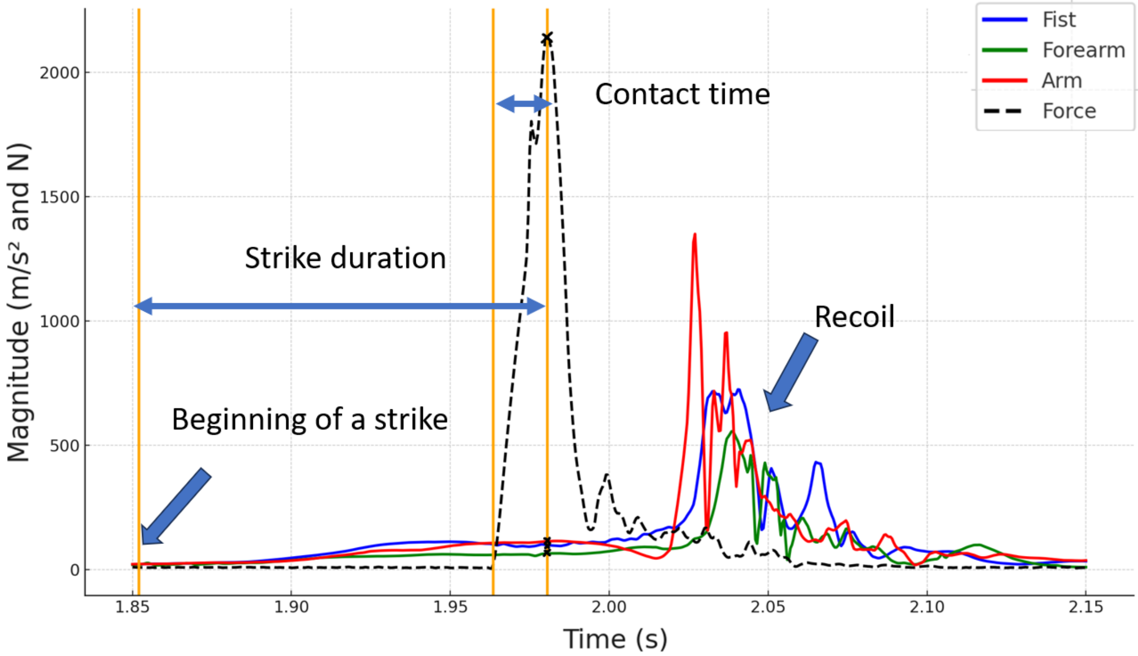

Figure 4. An example graph of impact force and acceleration during one impact. The vertical straight line marks a point of capturing values of acceleration for maximum force value.

Following data collection, which included maximum force values on the platform and changes in hand acceleration, the information was organized in Excel using Microsoft Office Professional Plus 2010, categorizing it by strike type and left or right arm. Consequently, data aimed for 130 measurement positions (13 individuals × 5 strikes × 2 arms), but we were able to extract 111 strikes.

For the purposes of statistical analysis, the data were exported to Statistica 13 software (TIBCO Software Inc., Santa Clara, CA, USA). Subsequent calculations included basic descriptive statistics and the Shapiro–Wilk test was conducted to assess normality. The Mann–Whitney U-test was employed to determine the significance of differences between groups. Additionally, Spearman's correlation coefficients were calculated to ascertain the presence of interdependencies between the variables under examination. Statistical significance was set at $p < 0.05$.

Based on the results of the Shapiro–Wilk test, with a significance level of $\alpha = 0.05$, we rejected the hypothesis of normal distribution for the variables 'age', 'body mass', 'height', 'training tenure', 'total GRF', 'afist', 'aforearm', and 'aarm', as all p-values were less than 0.0001.

To establish the necessary sample size for our study, we performed an a priori power analysis (G*Power) employing the Mann–Whitney U-test. This non-parametric test is appropriate for comparing two independent samples when the normality of the data cannot be assumed. Our analysis targeted the detection of a medium effect size (Cohen's d = 0.5), with a significance level (alpha) of 0.05 and a desired power of 0.8 (beta = 0.2). These parameters indicated an approximate sample size of 77 trials per group for achieving sufficient statistical power.

Our dataset consisted of measurements from 13 participants, but we analyzed 111 strikes (events, movements), with each represented by a single, unique dataset row. Variables include total ground reaction force (Total_GRF) and the acceleration of the fist (afist), forearm (aforearm), and arm (aarm). This sample exceeds the estimated requirement from our power analysis, providing confidence that our study has the power to reliably detect the specified effect size.

3. Results

In the recorded measurements, significant differences were noticed between the rear-cross and lead-jab strikes. There are statistically significant differences in the measurements of pressure force (Total GRF) as well as fist and forearm accelerations. Statistically significant differences between the techniques were also observed in measurements of arm acceleration and target contact time.

The range of total GRF results ranged from 670.04 N to 1748.19 N, with an average value of 1176.55 N for the lead jab, and from 1082.48 N to 2866.76 N, with an average of 1709.28 N for the rear cross. The time of fist contact with the target averaged 0.03 s for the rear cross and 0.02 s for the lead jab, with the highest recorded values being 0.17 s and 0.15 s, respectively. The lowest values oscillated around 0.01 s. The duration of the strike averaged 0.17 s for the rear cross and 0.18 s for the lead jab, with the smallest speeds being 0.08 s and 0.07 s, respectively, and the highest being 0.20 s for both techniques. The acceleration times for the rear cross averaged 94.33 m/s^2 for the fist, 67.11 m/s^2 for the forearm, and 88.40 m/s^2 for the arm. For the lead jab, these were, respectively, 66.07 m/s^2 for the fist, 41.62 m/s^2 for the forearm, and 81.36 m/s^2 for the arm (Table 1).

Table 1. Descriptive statistics of registered variables.

Indicator	Strike	Mean ± SD	Median	Lower Quartile	Upper Quartile	Range	Z	*p*	CV%	CI 95% Lower	CI 95% Upper
Pressure force	RC	1709.3 ± 486.6	1594.9	1339.8	2099.8	2866.8 ÷ 1082.5	−6.062 *	<0.0018 *	32.3	25.5	39
	LJ	1176.6 ± 248.7	1163.8	1010.8	13645	1748.2 ÷ 670					
Fist acceleration	RC	94.3 ± 18.5	95.3	78.9	103.4	174.2 ÷ 68.3	−6.379 *	<0.001 *	29.8	23.6	36
	LJ	66. ± 19.5	61.4	47.7	78.1	114.7 ÷ 36.3					
Forearm acceleration	RC	67.1 ± 25.3	65.8	47.2	81.4	146.7 ÷ 34.3	−5.959 *	<0.001 *	42.8	33.9	51.7
	LJ	41.6 ± 11	39.2	34.6	49	65.3 ÷ 22.5					
Arm acceleration	RC	88.4 ± 19.2	90.2	78.1	102.4	123.5 ÷ 47.7	−2.284 *	0.022 *	29.4	23.3	35.5
	LJ	81.4 ± 28.8	79.1	64.8	96.1	206.5 ÷ 28.6					

RC—Right-hand, LJ—lead-jab, SD—standard deviation, Z—Z score, *p*—The *p*-value in hypothesis testing, CV—Coefficient of Variation, CI—Confidence Interval, *—$p < 0.05$.

In the exploration of acceleration patterns across the upper limb from the proximal-to-distal segments, our analysis employed a polynomial trend analysis and visual inspection. Specifically, we assessed acceleration values across the arm (proximal), forearm (middle), and fist (distal) to investigate the hypothesized pattern of decreasing acceleration from the proximal to distal segments, which aligns with biomechanical expectations of movement efficiency and energy transfer in human limbs. Descriptive statistics of the boxplot presented in Figure 5 are presented in Table 1, with the median and range of presented values. The linear regression applied to these data segments revealed a slight negative slope (−2.67), suggesting a trend where acceleration values decrease from the proximal segment toward the distal segment. However, this observed trend did not reach statistical significance ($p = 0.146$), indicating that the data do not provide strong evidence for a consistent proximal-to-distal decrease in acceleration values across the studied segments (Figure 5).

In the examination of intersegmental dynamics and their influence on total ground reaction force (Total_GRF) within the context of upper limb movements, our analysis focuses on the acceleration patterns across the distal (fist), middle (forearm), and proximal (arm) segments. Utilizing a binary categorization based on median acceleration values, we delineated combinations of acceleration patterns and investigated their impact on Total_GRF, providing a nuanced understanding of the biomechanical efficiency across the upper limb. The analysis identified the "1-1-1" acceleration pattern, representing high acceleration in all three segments (fist, forearm, and arm), as yielding the highest

Total_GRF, with a peak value of approximately 2866.76 N. Conversely, the "1-0-1" pattern, denoting high acceleration in the distal and proximal segments but low acceleration in the middle segment (forearm), resulted in the lowest observed Total_GRF, with a value of approximately 1643.56 N (Figure 6).

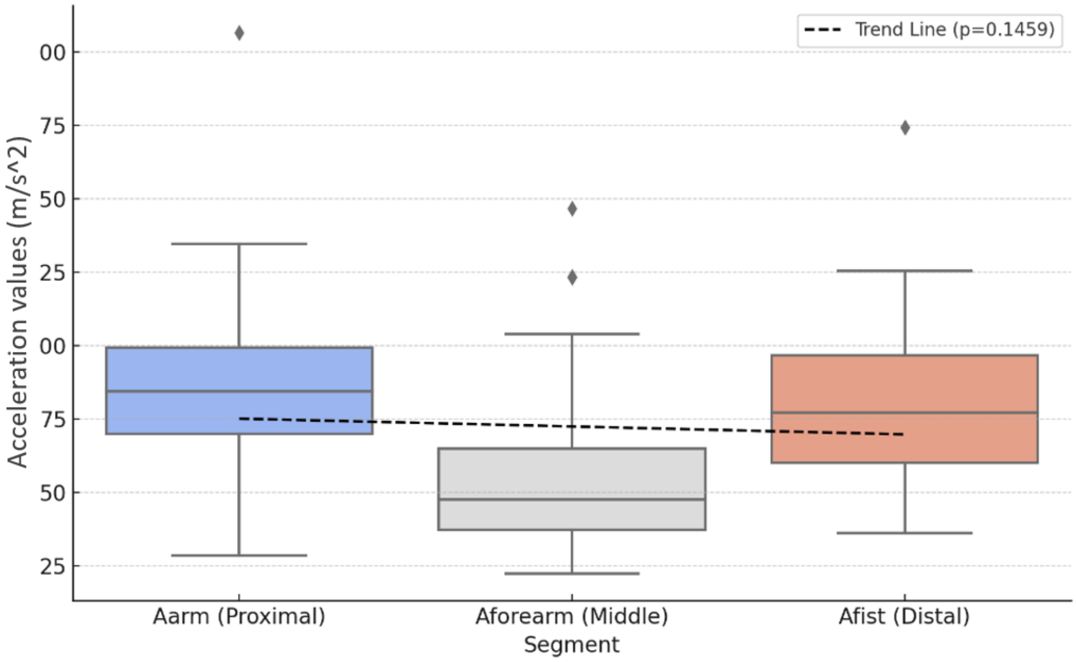

Figure 5. Proximal-to-Distal Acceleration Patterns in Upper Limb Segments with Polynomial Trend Analysis.

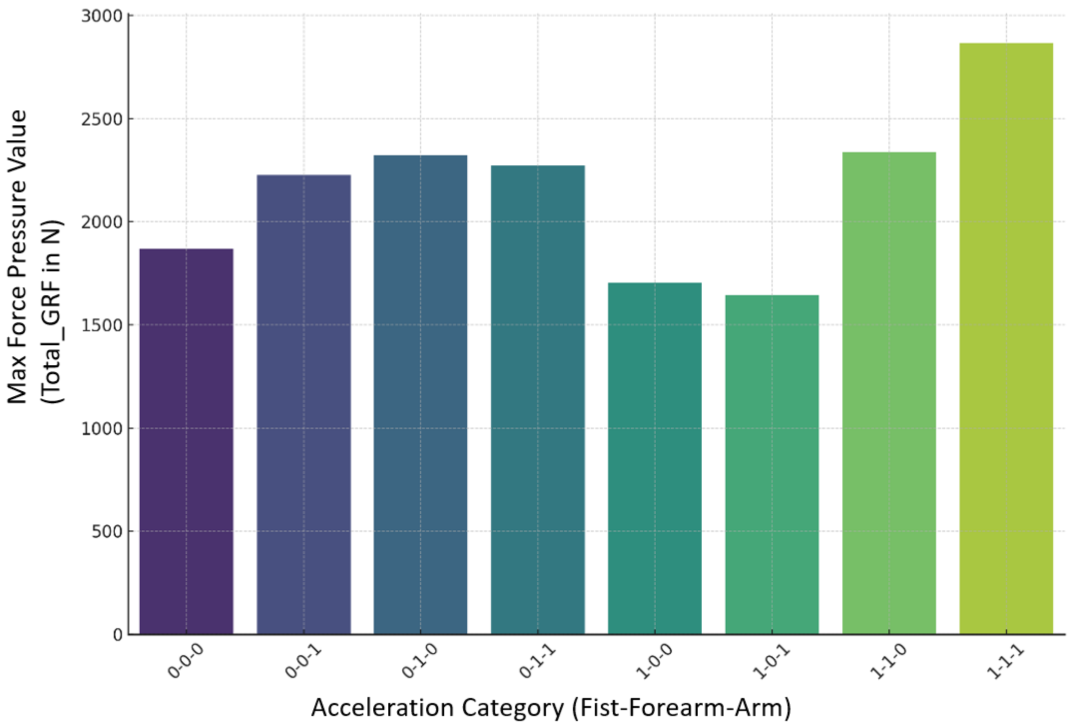

Figure 6. Max Total Ground Reaction Force Across Combined Acceleration Categories of Upper Limb Segments.

In examining the effects of various predictors on total ground reaction force (Total_GRF), identified as a key measure of force in boxing dynamics, a multiple regression analysis was conducted. The analysis, detailed in the accompanying dataset, reveals a robust model fit, evidenced by an R-value of 0.801 and an R^2 of 0.642. This indicates that approximately 64.2% of the variance in Total_GRF can be attributed to the predictors included in the model. The adjusted R^2, refined to 0.610 to account for the number of predictors, further underscores the model's capacity to elucidate the determinants of Total_GRF. The model's overall significance is confirmed by a high F-statistic value of 19.928 (df = 9, 100, $p < 0.00001$), validating the predictive power of the regression model.

The regression coefficients, as outlined in the results, provide insight into the individual contributions of each predictor. Notably, fist acceleration (afist) emerges as a statistically significant predictor, with a coefficient of 13.290 ($p < 0.001$), underscoring a pronounced positive relationship with Total_GRF. Body mass is also identified as a significant factor, with a coefficient of 10.491 ($p < 0.001$), indicating its influential role in force generation. Furthermore, training tenure, with a coefficient of 15.662 ($p = 0.035$), is highlighted as a key contributor to Total_GRF, suggesting the impact of experience and conditioning on force output.

Conversely, other variables such as forearm acceleration (aforearm) and arm acceleration (aarm), with coefficients of −0.145 and −0.266, respectively, did not achieve statistical significance, indicating a minimal direct impact on Total_GRF within the model's framework. Similarly, variables like body height, despite a positive coefficient of 7.332, did not reach statistical significance ($p = 0.214$), pointing to a less pronounced influence on Total_GRF (Table 2).

Table 2. Multiple Regression Analysis Results for Total_GRF (pressure force).

Indicator	Coefficient (b*)	Std. Error of b*	Coefficient (b)	Std. Error of b	t(100)	*p*-Value
Intercept	-	-	−2642.187	934.245	−2.828	0.006 *
Fist Acceleration	0.679	0.101	13.29	1.986	6.693	<0.001 *
Forearm Acceleration	−0.007	0.093	−0.145	1.878	−0.077	0.938
Arm Acceleration	−0.014	0.081	−0.266	1.498	−0.178	0.859
Target Contact Time	0.064	0.067	1153.517	1206.245	0.956	0.341
Strike Duration (s)	0.165	0.066	2231.891	891.515	2.503	0.014 *
Age	0.133	0.103	7.798	6.013	1.297	0.198
Body Mass	0.415	0.104	10.491	2.634	3.984	<0.001 *
Body Height	0.121	0.097	7.332	5.867	1.25	0.214
Training Tenure	0.198	0.093	15.662	7.334	2.135	0.035 *

Note: The dependent variable is Total_GRF. The model's overall fit statistics are R = 0.801, R^2 = 0.642, Adjusted R^2 = 0.610; F(9,100) = 19.9, * $p < 0.001$, with a standard error of the estimate at 289.3.

4. Discussion

Although both the lead jab and the rear cross are considered straight punches, their execution techniques differ significantly in terms of biomechanics. The lead jab is a fast punch, typically initiating combinations—its speed partly arises from the short distance between the extended front hand and the target. Typically, it aims to open the opponent's guard and create space for the rear-cross punch, which differs significantly in terms of kinetic properties. Through body rotation and engagement of greater mass and more body segments, the rear cross is able to generate significantly greater Total_GRF. Additionally, it turns out that accelerations occurring with the rear cross can be greater than with the lead jab, which could also be due to the additional torso rotation [16].

In practice, the biomechanical differences between these two punches have a significant impact on their effectiveness and application in combat. The lead jab, with its speed and ability to open the guard, can be used to control distance and initiate attacks, while the rear cross, with its strength and power generated by body rotation, may be more effective in inflicting serious damage and finishing a fight. Understanding these biomechanical differences allows a boxer to better utilize each of these punches depending on the situation and the objective of the attack [17] It is recommended that athletes enhance their training process with advanced technique exercises, especially incorporating body rotation during striking, as this can lead to higher fist acceleration values.

The total ground reaction force averaged 1709.28 ± 486.62 N for the rear cross and 1176.55 ± 248.69 N for the lead jab. The highest recorded values of force were 2866.76 N for the rear cross and 1748.19 N for the lead jab. Therefore, significant differences in striking force between these two techniques were observed. However, considering that the study participants were elite athletes with a high level of training, their results may not fully represent their potential. In studies by Daniel Dinu and Julie Louis, a group of elite boxers achieved a result of 3158 ± 1467 N for the rear cross [5]. Meanwhile, Yang Liu's striking force for the lead jab was 1507.99 ± 411 N [18]. Chadli [19] reported the peak strength observed ranged from 761 to 1162 N, which is below the values reported by Walilko [20], which lie between 1990 and 4741 N, and also lower than the findings of Dyson [21], where strength varied from 2471 to 4236 N. Such large differences could be due to the measurement method—in the aforementioned studies, athletes used a fist in a boxing glove. The surface area of the glove is larger than that of the fist, and the striking force could be distributed more evenly. Striking with an uncovered fist is point-specific. Additionally, the shock-absorbing properties of the boxing glove may also have caused athletes to strike with greater force. When striking with a bare fist, participants in the study may have intuitively struck more cautiously. Boxers aiming to increase their force should incorporate more strength exercises into their training regimen, particularly focusing on explosive power. This can significantly enhance the power behind their strikes if they can efficiently integrate their strength to produce sufficient acceleration of their limbs.

Both the average fist acceleration and the average accelerations of the forearm and arm were higher in the case of the rear-cross punch than in the case of the lead-jab punch, which apparently seems faster. This may be due to greater torso rotation and shoulder girdle involvement, which allow for greater acceleration values to be generated. Comparing the results to the works of other researchers is difficult, as most of them operate on velocities rather than accelerations. All researchers made their own measurement instrument setups just like us, with a custom force measurement system, and measured acceleration in their own manner. As such, it is hard to compare such results, as different setups led to different outcomes. Tiwari et al. measured acceleration on their device at a level between 25 and 35 m/s^2 and a peak force of 250 N. Those results are significantly lower than ours. However, their methods' description did not provide sufficient information about the moment of acceleration detection [22]. In other studies, Chadli et al. measured fist acceleration from 24 g to 30.2 g (where g stands for acceleration of gravity at 9.81 m/s^2), which is almost twice as much as in our study. Again, the moment of determining this acceleration was not stated. In Figure 3, we showed how acceleration rises through full technique execution. The highest acceleration measurements were after the maximum peak of force; therefore, in their studies, the stated results might have been for after impact [19]. The same methodology could also be applied by Walilko et al., but this time, there was an expert-level group, with acceleration after impact from 33 to 78 g [20].

The study results do not fit into the proximal–distal pattern. Acceleration values decreased slightly from the proximal segment to the distal segment, as depicted by a linear regression with a negative coefficient (−2.67). However, despite this observed trend, the statistical analysis did not show statistical significance (p = 0.146), suggesting that the data do not provide strong evidence for a consistent decrease in acceleration values across the studied segments.

This inconsistency between the decrease in acceleration and the lack of statistical significance may stem from subtle differences in the way participants executed movements during the study and potential methodological limitations. Additionally, the influence of other factors, such as individual differences in anatomy and level of physical fitness, could be also significant for the results. The proximal–distal pattern has been confirmed in other studies examining kinematic analysis of taekwondo kicking techniques [13] It has also been observed in a study on straight punches executed by elite Wing Chun practitioners [12]. However, both of these disciplines significantly differ from boxing, including in the biomechanics of the executed strikes.

From the measurements, it can also be inferred that when all three body segments are in the upper quartile, it means that the entire body is engaged in the activity, and the proximal segments (closer to the body's center) generate greater force and energy, which is transferred to the more distal segments (further from the body's center). In the context of achieving the highest force values on the target, this could mean that the full utilization of the entire body, according to the proximal–distal model, leads to maximal force generation during the strike. Implementation of advanced body coordination exercises, even beyond boxing training but focused on whole-body movement, could lead to improving athletes' fist acceleration and overall strike dynamics.

However, disruptions in this sequence, meaning situations where body segments are not in the correct positions, can result in lower force values on the target. For example, if the proximal segments do not generate sufficient force or are not well synchronized with the distal segments, the force transferred to the target may be weakened or inadequate. Effective utilization of the entire body, starting from the segments closest to the body's center, which generate force and energy, down to the more distant segments, could lead to the highest force values being achieved during the striking of the target.

Therefore, while certain trends were observed in the analysis of acceleration patterns within the upper limb, caution should be exercised in interpreting these results. Further research, involving a larger number of participants, may be needed to better understand the complex relationships between segments of the upper limb and movement dynamics.

Regression model analysis of recorded results reveals both statistically significant and insignificant predictors. Fist acceleration and body mass emerged as significant factors, with their positive impact on total ground reaction force (Total_GRF) confirmed by low p-values, respectively, $p < 0.001$ for both predictors. Higher values of fist acceleration were correlated with greater force exerted on the target, possibly due to higher fist velocity during the strike. Similarly, greater body mass was associated with higher striking force. However, there were variables that did not prove to be statistically significant in the model. Forearm acceleration and arm acceleration showed no significant impact on Total_GRF, suggesting their minimal role in force generation compared to other factors. Likewise, body height was not significant, indicating that height may not have a significant influence on striking force in the analyzed context.

An interesting finding from the analysis is the significant impact of training tenure on Total_GRF, supported by low p-values ($p = 0.035$). This implies that experience and training time significantly affect striking force. Individuals with longer training tenure may be more effective in generating force, potentially due to greater strength, acceleration-generating ability, and technique acquired during training. Regression analysis identified significant factors shaping Total_GRF in the context of boxing. Despite some limitations, such as the insignificance of certain variables, the model provides valuable insights into the determinants of striking force. Particularly noteworthy is the confirmation of the importance of experience and training tenure in generating striking force.

The study had certain limitations that could have influenced the presented results. It involved only 13 participants. Although this number allows for observing certain patterns, it still does not provide a broad perspective on boxers as a whole. Expanding the research to include more participants could improve the reliability of the results. Additionally, the rigid target installed on the force plate is not a typical striking target in the context of the studied discipline. Boxers accustomed to striking heavy punching bags could expect different cushioning properties from the target. Striking a hard target with a bare fist, without gloves, may have caused participants to strike with caution involuntarily, not utilizing their full power potential. Another limitation was the small number of sensors—they were only placed on the fist, forearm, and arm of the participant. Increasing the number of sensors and placing them on the shoulder, collarbone, and sternum would allow for a more precise examination of acceleration values during lead-jab and rear-cross techniques and a more detailed examination of them in terms of the occurrence of the proximal–distal pattern.

The conducted study provides numerous insights and recommendations for both athletes and coaches, as well as biomechanical researchers in boxing. As inferred in previous studies [18], boxers can enhance their striking force by focusing on increasing fist acceleration and body mass. Training programs should prioritize exercises that develop speed and power in punching techniques and incorporate strength training to increase body mass [23]. Experienced boxers could leverage their training tenure to refine their striking technique and optimize force generation. Consistent practice and exposure to diverse training scenarios could further enhance their ability to deliver powerful strikes. Coaches could consider incorporating drills that enhance speed, strength, and coordination specific to each punch, thereby increasing the effectiveness of the athlete. Analyzing individual boxers' strengths and weaknesses in executing lead jabs and rear crosses can lead to personalized training programs. Coaches should provide targeted feedback and corrective exercises to address technical deficiencies and maximize force generation. Future research in the field of biomechanics of straight punches should aim to address the limitations identified in this study, such as small sample size and sensor placement [15]. Conducting studies with larger and more diverse participant groups and utilizing comprehensive sensor arrays can provide a more comprehensive understanding of boxing biomechanics.

5. Conclusions

Research indicates significant kinetic differences between the lead-jab and rear-cross punches in boxing. The rear cross exhibits greater total ground reaction force (GRF), fist acceleration, and target contact time, demonstrating its superior power generation. This is attributed to the rear cross's incorporation of greater body rotation and engagement of multiple body segments. Interestingly, the rear cross achieves higher acceleration than the lead jab despite the latter being perceived as faster, likely due to the added rotational force.

While a proximal-to-distal acceleration decrease across upper limb segments was hypothesized, the study found no statistically significant support for this pattern. Boxer body mass and training experience were positively correlated with total GRF, emphasizing the importance of strength and conditioning in optimizing striking force.

These findings suggest that maximizing fist acceleration and body mass is critical for increasing punch power. Coaches and athletes should design training regimens that specifically target these components, along with technical refinement, to enhance the force generation of both lead-jab and rear-cross punches.

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