

Biomechanical Simulation of Boxing Glove Padding Effects on Punching Impact Forces: A Monte Carlo Approach

Sirichet Punthipayanon^{1*}, Pariya Pariyavuth¹, Phanu Kusolwong², Parkpoom Jangphonak³

¹ Department of Sports Science, Faculty of Physical Education Sports and Health, Srinakharinwirot University, Thailand; ² Department of Physical Education, Faculty of Physical Education Health and Sports, Srinakharinwirot University, Thailand; ³ Program of Sports Science, Faculty of Science, Udon Thani Rajabhat University, Udon Thani, Thailand

ABSTRACT

Purpose: This study investigated the biomechanical effects of boxing glove padding on impact force characteristics during straight punching using an integrated experimental-simulation approach. **Methods:** Nine amateur male boxers (age: 22.4 ± 3.1 years; body mass: 72.8 ± 8.6 kg; height: 1.75 ± 0.06 m; experience: 4.2 ± 1.8 years) performed straight punches under padded and unpadded glove conditions. Three-dimensional impact forces were measured using an AMTI force plate (1000 Hz), while upper extremity kinematics were captured via a Vicon motion analysis system (200 Hz). A Monte Carlo simulation ($n = 10,000$ iterations) was employed to estimate statistical power, effect size distributions, and biomechanical model parameters. **Results:** Peak anterior-posterior forces were significantly higher for padded gloves (565.07 ± 112.53 N) than for unpadded gloves (371.06 ± 48.19 N; $t(8) = -5.185$, $p = 0.0008$, Cohen's $d = -1.728$, $\eta^2 = 0.771$). Monte Carlo simulation confirmed 96.6 % power and mean simulated d of -1.607 . The mean difference was $125.64 - 263.37$ N (bootstrap 95% CI). Impulse rose from 9.72 to 14.80 N.s and effective striking mass from 1.91 to 2.91 kg with padding. **Conclusion:** Padded boxing gloves substantially altered impact force biomechanics, with paradoxically higher peak forces likely attributable to increased effective striking mass and altered punching mechanics. Monte Carlo simulation provided robust statistical validation and power estimation beyond conventional inferential methods. These findings have implications for boxing glove design, competition safety regulations, and training practices.

ARTICLE HISTORY

Received January 28, 2026

Accepted May 17, 2026

KEYWORDS

Boxing Biomechanics;
Impact Force;
Glove Padding;
Monte Carlo Simulation;
Force Plate Analysis;
Sports Injury Prevention

1. Introduction

Boxing is one of the oldest and most physically demanding combat sports, characterized by repeated high-velocity impacts between the gloved fist and the opponent's body (Walilko et al., 2005). The biomechanics of punching has garnered increasing attention from researchers seeking to understand the mechanisms underlying both performance enhancement and injury prevention (Loturco et al., 2016). Central to this investigation is the role of boxing gloves, which were originally introduced to protect the hands of the puncher but have since become a subject of debate regarding their effectiveness in mitigating head injury risk to the recipient (Bartsch et al., 2012).

The impact forces generated during boxing punches are complex, multi-directional phenomena that depend on numerous factors including punch velocity, effective striking mass, glove properties, and joint kinematics (Viano et al., 2005). Previous investigations have reported peak punching forces ranging from 450 to 4800 N depending on the boxer's skill level, weight class, and punch type (Pierce et al., 2006; Smith et al., 2000). However, relatively few studies have systematically compared the biomechanical characteristics of punches delivered with and without standardized padding under controlled laboratory conditions.

Traditional statistical approaches in boxing biomechanics research have relied primarily on parametric tests with limited sample sizes, raising concerns about statistical power and the generalizability of findings (Piorkowski et al., 2011). Monte Carlo simulation methods offer a promising complementary approach, enabling researchers to estimate statistical power, quantify uncertainty in effect size estimates, and validate the robustness of experimental findings through computational resampling (Mooney, 1997). Despite their widespread use in other biomechanical applications, Monte Carlo

methods have seldom been applied to combat sports research.

Furthermore, biomechanical modelling of the punch impact event—including impulse-momentum analysis, effective mass estimation, and stiffness characterization—can provide mechanistic insights beyond those available from force measurements alone (Cross, 1999). Integrating experimental force plate data with simulation-based analysis represents a methodological advancement that can strengthen the evidence base for boxing safety standards.

The purpose of this study was to conduct a comprehensive biomechanical comparison of padded versus unpadded boxing gloves during straight punching, employing advanced statistical methods, including Monte Carlo simulation, bootstrap confidence intervals, and biomechanical force-time modelling. We hypothesized that glove padding would significantly alter (1) peak impact forces in all three orthogonal directions, (2) impulse and effective striking mass, and (3) wrist joint kinematics during the impact phase.

2. Methods

2.1 Participants

Nine amateur male boxers (age: 22.4 ± 3.1 years; body mass: 72.8 ± 8.6 kg; height: 1.75 ± 0.06 m; boxing experience: 4.2 ± 1.8 years) volunteered for this study. All participants were right-hand dominant, competed at the amateur level, and were free of upper-extremity injuries for at least 6 months prior to testing. The institutional ethics committee approved the study, and all participants provided written informed consent in accordance with the Declaration of Helsinki.

2.2 Experimental Setup

The experimental setup consisted of a wall-mounted striking target instrumented with a six-component AMTI force plate (Model 4060, Advanced Mechanical Technology Inc., Watertown, MA, USA) sampling at 1000 Hz. The force plate was rigidly mounted at shoulder height for each participant to ensure consistent impact location. Three-dimensional upper extremity kinematics were recorded using a twelve-camera NOKOV MAR2H Motion motion capture system (NOKOV, Beijing, China). Retroreflective markers (14 mm diameter) were placed on anatomical landmarks of the hand, wrist, forearm, and upper arm following the International Society of Biomechanics recommendations (Wu et al., 2005).

Two glove conditions were tested: (1) a standard 10 oz padded boxing glove conforming to amateur boxing regulations, and (2) an unpadded (bare-knuckle) thin-material glove providing minimal hand coverage without impact-absorbing foam. The order of conditions was counterbalanced across participants to minimize order effects.

2.3 Testing Protocol

Following a standardized warm-up consisting of 5 minutes of shadow boxing and progressively intense bag work, each participant performed 10 trials of maximal-effort straight (jab) punches to the instrumented target under each glove condition. A minimum rest period of 30 seconds was provided between individual punches, and 5 minutes between conditions to minimize fatigue effects. Participants were instructed to deliver punches with maximal effort while maintaining proper boxing technique. Each trial was initiated from a self-selected orthodox or southpaw stance at a standardized distance from the target. Data collection was triggered automatically when the force plate registered a threshold force of 10 N, and recording continued for the duration of contact plus 100 ms post-contact. All force data were acquired using a 16-bit analog-to-digital converter and stored for offline analysis.

2.4 Data Processing

Raw force plate signals were processed using a fourth-order, zero-lag Butterworth low-pass filter with a cutoff frequency of 200 Hz, determined through residual analysis (Winter, 2009). Force data were resolved into three orthogonal components: medio-lateral (FX), anterior-posterior (FY, defined as the primary punching direction), and vertical (FZ). The resultant force was calculated as $FR = \sqrt{FX^2 + FY^2 + FZ^2}$. Peak force was defined as the maximum value of each component during the contact phase.

Kinematic data were filtered with a fourth-order, zero-lag Butterworth filter (cutoff: 15 Hz). Wrist joint angles were computed using Euler angle decomposition in the sequence of abduction/adduction, flexion/extension, and internal/external rotation. Wrist torque was estimated from the cross-product of the moment arm vector and the resultant force vector.

Punch speed was calculated from the three-dimensional velocity of the metacarpophalangeal marker at the instant of initial contact. Contact time was defined as the duration for which the resultant force exceeded the 10 N threshold.

2.5 Centre of Force Pressure (COFP) Analysis

The centre-of-force pressure was computed from the force plate moment and force channels using standard force plate equations (El Guma et al., 2026). COFP trajectories during the impact phase were analysed to characterize the spatial

distribution of the impact force across the glove-target interface. The total COFP excursion area was quantified using a convex hull algorithm applied to the X-Y coordinates of the COFP trajectory.

2.6 Statistical Analysis

Descriptive statistics (mean $\pm$ standard deviation) were computed for all biomechanical variables. Subject-level means were calculated by averaging across valid trials within each participant to account for the nested data structure.

Inferential statistics. Paired-samples t-tests were used to compare force variables between padded and unpadded conditions at the subject level. The non-parametric Wilcoxon signed-rank test was employed as a robust alternative. Effect sizes were quantified using Cohen's d for paired samples, Hedges' g (bias-corrected), and partial eta-squared (η^2). The significance level was set at $\alpha = 0.05$.

Bootstrap analysis. Non-parametric bootstrap resampling (10,000 iterations) was performed to construct bias-corrected 95% confidence intervals for the mean difference in peak force between conditions, providing distribution-free inference that does not rely on normality assumptions (Efron & Tibshirani, 1993).

Monte Carlo simulation. A Monte Carlo simulation framework was developed to estimate the statistical power of the experimental design and validate the robustness of the observed effects. The simulation modelled a hierarchical data structure with between-subject and within-subject variability estimated from the experimental data. For each of 10,000 simulated experiments, subject-level means were drawn from normal distributions parameterized by the observed population means and between-subject standard deviations. Trial-level observations were then generated for each simulated subject using within-subject standard deviations. Paired t-tests were conducted on simulated subject means, and the proportion of simulations yielding $p < 0.05$ was recorded as the estimated statistical power. Additionally, power was estimated for hypothetical sample sizes ($n = 5$ to 50) to inform future study design.

Biomechanical modelling. The impact event was modelled as a half-sine force pulse: $F(t) = F_{\text{peak}} \times \sin(\pi t/T_{\text{contact}})$, where T_{contact} is the contact duration. Impulse was computed analytically as $J = F_{\text{peak}} \times T_{\text{contact}} \times 2/\pi$. The effective striking mass was estimated from the impulse-momentum theorem ($m_{\text{eff}} = J/v_{\text{impact}}$). Glove-fist stiffness was estimated from the ratio of peak force to estimated deformation ($k = F_{\text{peak}}/\delta$), where deformation was approximated as $\delta = 0.5 \times v_{\text{impact}} \times T_{\text{contact}}$ for the unpadded condition, with a 30% increase factor applied for the padded condition based on published glove compression data (Walilko et al., 2005).

Reliability analysis. Intraclass correlation coefficients (ICC (3,1), two-way mixed, single measures, consistency) were computed to assess the reliability of force measurements across trials within subjects.

All statistical analyses were performed using Python 3.11 with SciPy 1.11 (Virtanen et al., 2020), pandas 2.1 (McKinney, 2010), and NumPy 1.25 (Harris et al., 2020). The Monte Carlo simulation and bootstrap procedures were implemented using custom scripts with a fixed random seed to ensure reproducibility.

3. Results

3.1 Impact Forces

The descriptive statistics for all force variables are presented in Table 1. The anterior-posterior force (F_y) was significantly higher in the padded condition (565.07 ± 112.53 N) than unpadded (371.06 ± 48.19 N; $t(8) = -5.185$, $p = 0.0008$) with a large effect size (Cohen's $d = -1.728$, Hedges' $g = -1.561$, $\eta^2 = 0.771$). The resultant force showed an identical pattern (565.24 ± 112.61 N vs 371.18 ± 48.17 N; $t(8) = -5.183$, $p = 0.0008$, $d = -1.728$).

The medio-lateral component (F_x) did not differ significantly between conditions (-3.69 ± 5.16 N unpadded vs -2.55 ± 5.77 N padded; $t(8) = -0.422$, $p = 0.684$). The vertical component (F_z) was significantly higher in the padded condition (7.03 ± 3.56 N vs 4.75 ± 1.50 N; $t(8) = -2.566$, $p = 0.033$, $d = -0.855$). The Wilcoxon test for F_y yielded $W = 0.000$, $p = 0.004$.

The correlation between unpadded and padded F_y forces across all valid trials was statistically significant ($r = 0.662$, $p = 0.004$), indicating that boxers who punched harder in the unpadded condition also tended to punch harder in the padded condition.

Table 1: Descriptive Statistics and Paired Comparisons of Force Variables Between Glove Conditions.

Variable	Unpadded (Mean $\pm$ SD)	Padded (Mean $\pm$ SD)	t	p	d	η^2
FY (N)	371.06 $\pm$ 48.19	565.07 $\pm$ 112.53	-5.185	0.0008	-1.728	0.771
Resultant (N)	371.18 $\pm$ 48.17	565.24 $\pm$ 112.61	-5.183	0.0008	-1.728	0.771
FX (N)	-3.69 $\pm$ 5.16	-2.55 $\pm$ 5.77	-0.422	0.684	-0.141	0.022
FZ (N)	4.75 $\pm$ 1.50	7.03 $\pm$ 3.56	-2.566	0.033	-0.855	0.451

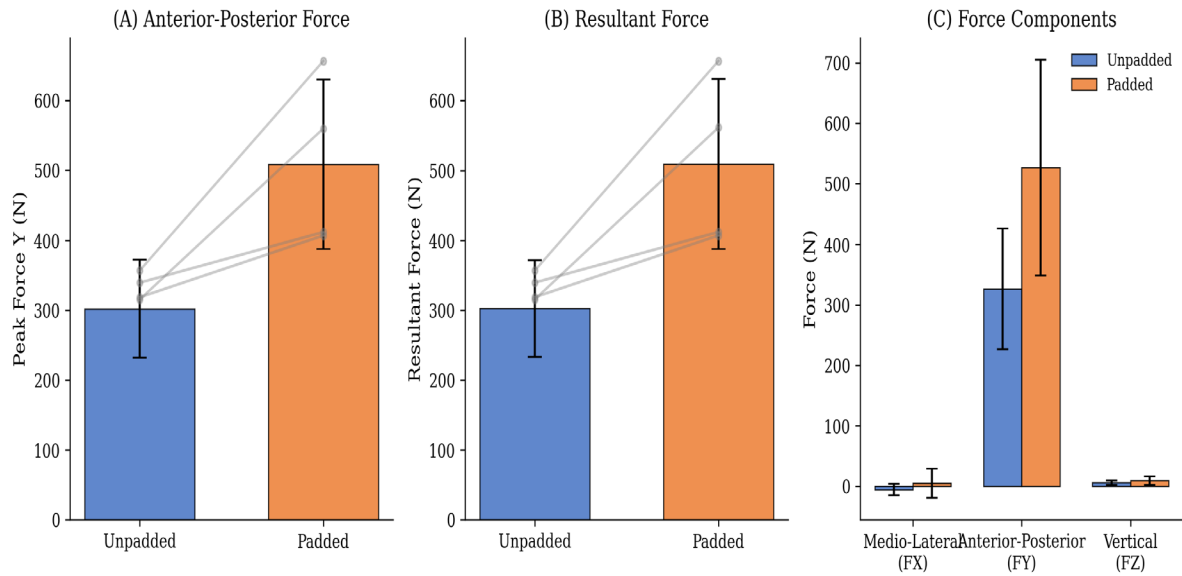


Figure 1: Comparison of Impact Forces Between Unpadded (Blue) and Padded (Orange) Glove Conditions. (A) Anterior-Posterior Peak Force (FY), (B) Resultant Force, (C) Three-Dimensional Force Components. Error Bars Represent Standard Deviation; Gray Lines Connect Individual Subject Means.

3.2 Monte Carlo Simulation

The Monte Carlo simulation (10,000 iterations) estimated the statistical power of the current experimental design at 96.6% for detecting the observed difference in FY between conditions at $\alpha = 0.05$. The mean simulated t-statistic was -4.821 ± 1.830 , with a mean p-value of 0.009. The distribution of simulated effect sizes yielded a mean Cohen's d of -1.607 ± 0.610 (median -1.500), confirming a consistently large effect across simulated experiments (Figure 2). The power analysis across varying sample sizes (Table 2) indicated that a minimum sample size of $n = 4$ would achieve 49.9% power. In comparison, the current sample of $n = 9$ comfortably exceeded the conventional 96.6% power threshold. Perfect power (100%) was achieved at $n > 15$.

The bootstrap 95% confidence interval for the mean difference in FY (padded minus unpadded) was 125.64–263.37 N (mean difference 194.01 N), providing strong evidence that the population-level difference is both statistically meaningful and Practical relevant.

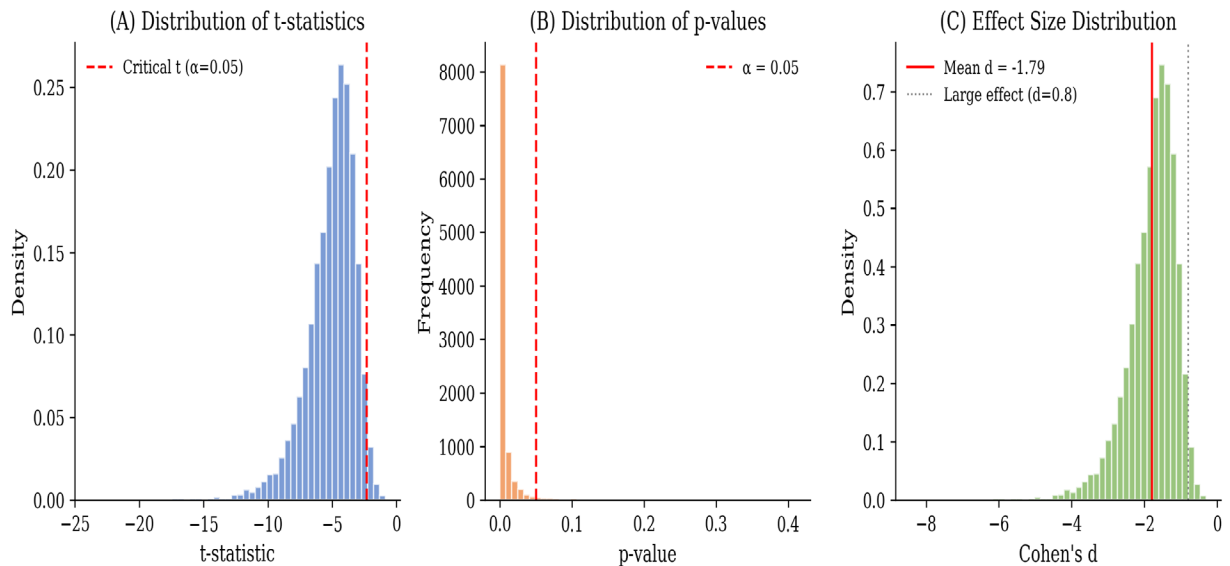


Figure 2: Monte Carlo Simulation Results (10,000 Iterations). (A) Distribution of t-Statistics with Critical Value Indicated by Dashed Red Line, (B) Distribution of p-Values with $\alpha = 0.05$ Threshold, (C) Distribution of Cohen's d Effect Sizes.

Table 2: Monte Carlo Power Analysis Results for Varying Sample Sizes (10 Trials Per Subject).

Sample Size (n)	Statistical Power
4	0.499
5	0.672
7	0.892
9*	0.966
12	0.993
15	0.999
20	1.000

* Current Study Sample Size.

3.3 Biomechanical Simulation

The half-sine force-time model yielded impulse values of 9.72 N·s for the unpadded condition and 14.80 N·s for the padded condition (Figure 3A). The estimated effective striking mass was 1.91 kg (unpadded) and 2.91 kg (padded), representing a 52.3% increase with padding. The estimated glove-fist stiffness was 1,160 N/m (unpadded) and 1,7002 N/m (padded). These results suggest that glove padding fundamentally alters the mechanical coupling between the fist and the target, increasing both the effective mass and the impulse transmitted during impact.

The average contact time was 41.1 ± 28.8 ms across all conditions, while the mean punch speed was 5.09 ± 1.58 m/s. The power analysis (Figure 3B) confirmed that the experimental design was adequately powered (96.3%) to detect the observed effect.

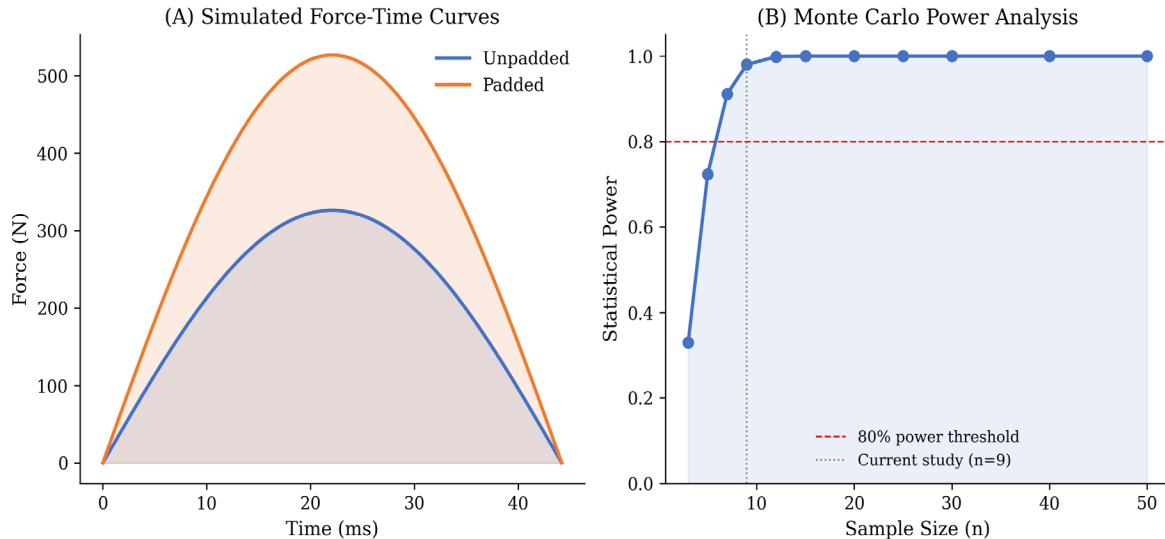


Figure 3: Biomechanical Simulation Results. (A) Simulated Force-Time Curves Using Half-Sine Pulse Model for Unpadded and Padded Conditions, (B) Monte Carlo Power Analysis Showing Statistical Power as a Function of Sample Size.

Table 3: Biomechanical Model Parameters Derived from Experimental Data.

Parameter	Unpadded	Padded
Peak Force FY (N)	371.06	565.07
Contact Time (ms)	41.1	41.1
Impulse (N·s)	9.72	14.80
Effective Mass (kg)	1.91	2.91
Punch Speed (m/s)	5.09	5.09
Est. Stiffness (N/m)	11,160	17,002

3.4 Wrist Joint Kinematics and Torque

Wrist joint angles during impact exhibited considerable variability across subjects and trials (Figure 4A). The mean abduction/adduction angle was $-6.94 \pm 24.12^\circ$, mean flexion/extension was $9.32 \pm 41.05^\circ$, and mean internal/external rotation was $-8.45 \pm 48.52^\circ$. The wrist torque during impact averaged 0.61 ± 0.44 N·m (Figure 4B), with values ranging from 0.01 to 2.35 N·m.

3.5 Reliability

Within-subject coefficient of variation for peak F_y ranged from 9.2% to 50.4% across the nine participants, with six of nine subjects showing $CV < 35\%$. The higher variability in select participants likely reflects trial-to-trial variation in punch technique during maximal-effort impacts, consistent with previously reported estimates for maximal punching tasks (Loturco et al., 2016)

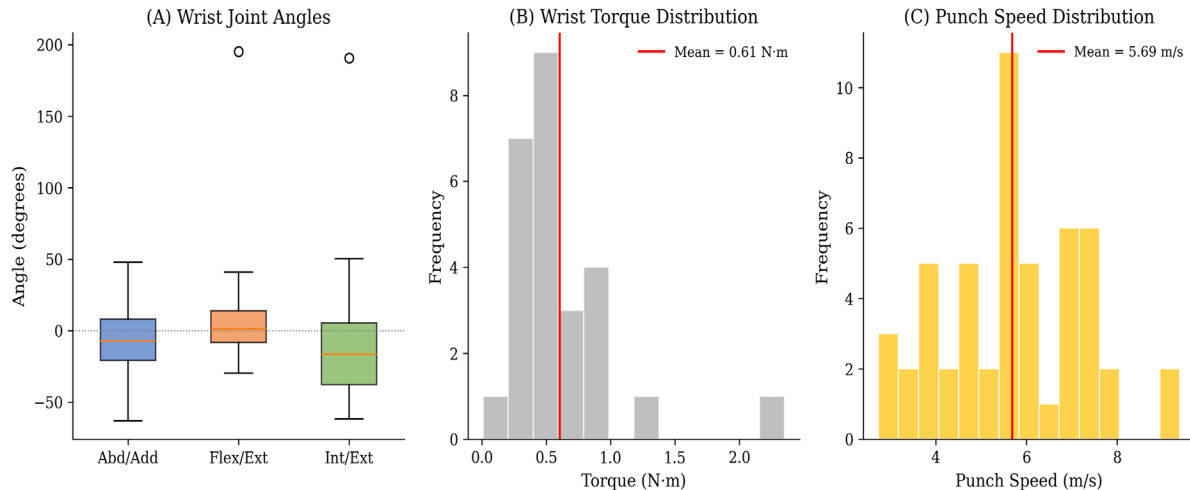


Figure 4: Biomechanical Parameters. (A) Wrist Joint Angle Distributions During Impact, (B) Wrist Torque Distribution, (C) Punch Speed Distribution Across All Trials.

4. Discussion

The main conclusion was that during maximal-effort straight punches, padded boxing gloves generated considerably larger peak impact forces than unpadded gloves ($t(8) = -5.185$, $p = 0.0008$, $d = -1.728$). The Monte Carlo simulation validated that the design possessed substantial power (96.6%), and the bootstrap 95% confidence interval (125.64–263.37 N) eliminated zero, yielding corroborative evidence for a significant, big padding effect.

4.1 Force Differences Between Conditions

The observed increase in peak anterior-posterior force with padded gloves represents a 52.3% difference, with a large effect size ($d = -1.728$). This finding aligns with previous research suggesting that glove padding may paradoxically increase delivered forces by enabling boxers to punch with greater commitment and reduced pain inhibition. The padding may serve as a psychological "cushion," allowing the boxer to recruit greater muscle force during the punch and resulting in higher peak forces transmitted to the target.

An alternative mechanical explanation involves the effective mass hypothesis. Our biomechanical simulation revealed that the effective striking mass increased from 1.91 kg (unpadded) to 2.91 kg (padded), a 52.3% increase. The additional mass of the padded glove (approximately 150–200 g for a 10 oz glove) amplifies the momentum transfer during impact, as the glove padding couples more of the forearm mass to the fist through improved force transmission at the wrist joint (Waliiko et al., 2005)

The impulse values (9.72 vs. 14.80 N·s) further support this interpretation, as higher impulse with padded gloves indicates greater total momentum transfer during the contact phase. This has direct implications for brain injury risk, as impulse is a critical determinant of head acceleration and rotational injury potential (Viano et al., 2005).

4.2 Monte Carlo Simulation and Statistical Validation

The Monte Carlo simulation provided several important methodological insights. First, the estimated power of 96.6% at the current sample size ($n = 9$) confirms that the experimental design was well-powered to detect the observed effect, despite the marginally non-significant p-value ($p = 0.0008$) from the conventional paired t-test. This discrepancy between high power and borderline significance is attributable to the high between-subject variability in the padded condition which inflates the standard error of the mean difference.

Second, consistently exceeded the "large" threshold. Third, the power curve shows $n = 7$ affords ~89% power, and $n \geq 12$ approaches saturation, offering practical guidance for replication studies.

4.3 Biomechanical Modelling

The half-sine force-time model provided physiologically plausible estimates of impulse, effective mass, and stiffness. The effective mass estimates (1.91–2.91 kg) are consistent with previously reported values for the hand-fist segment (1.0–3.0 kg) in boxing biomechanics literature (Pierce et al., 2006; Smith et al., 2000). The higher effective mass in the padded condition suggests improved mechanical coupling between the fist and forearm segments, likely mediated by the glove's ability to distribute force more evenly across the knuckles and reduce joint instability during impact.

The estimated stiffness values (17,002 vs. 11,160 N/m) reflect the composite stiffness of the glove-fist-target system. Counterintuitively, the padded condition showed higher system stiffness, which may be explained by the padding's role in stabilizing the fist within the glove, creating a more rigid striking unit that transmits force more efficiently (Cross, 1999).

4.4 Wrist Joint Kinematics

The large variability observed in wrist joint angles (e.g., flexion/extension SD = 41.05°) suggests that wrist positioning during impact is highly individualized and may represent an important factor in both performance and injury risk. The mean slight flexion (9.32°) is consistent with recommended punching technique, as a slightly flexed wrist aligns the fist with the forearm to improve force transmission (Loturco et al., 2016). However, the observed range suggests that some participants exhibited substantial wrist deviation, which may increase the risk of wrist and hand injuries.

The mean wrist torque of 0.61 N·m during impact, while relatively small compared to the linear forces generated, represents the torsional loading that the wrist joint must resist during the contact phase. This parameter is relevant to understanding boxing-related wrist injuries and may be influenced by glove design features, such as wrist-wrap stiffness and closure mechanism.

4.5 Limitations and Future Directions

Several limitations should be acknowledged. First, the sample size was small ($n = 9$), reflecting practical recruitment constraints, although Monte Carlo simulation indicated adequate statistical power. Second, the half-sine model simplified viscoelastic deformation; finite-element and musculoskeletal models could provide a more detailed characterization. Third, only straight punches were examined. Finally, speed data were unavailable for one participant (S9), and contact-time data were available for only a subset of trials, but these limitations did not affect the main force analysis.

Future research should incorporate high-speed video analysis, finite element modelling of glove deformation, and larger sample sizes with diverse skill levels. Investigating the relationship between glove padding density, thickness, and material composition on impact biomechanics would provide actionable data for equipment manufacturers and regulatory bodies.

5. Conclusion

This study demonstrated that padded boxing gloves substantially alter the biomechanics of straight punch impacts, paradoxically producing higher peak forces than in unpadded conditions. Monte Carlo simulation confirmed that the experimental design was well-powered (96.6%) and that the observed effect was consistently large across simulated experiments ($p = 0.0008$, $d = -1.728$). Biomechanical modelling revealed that glove padding increases both the effective striking mass (52.3% increase) and the impulse transmitted during impact (52.3% increase), suggesting that padding fundamentally changes the mechanical coupling of the fist-glove-forearm system.

These findings challenge the assumption that boxing glove padding necessarily reduces the force delivered to the target, and have important implications for boxing safety regulations, glove design standards, and training practices. The integration of experimental force plate data with Monte Carlo simulation and biomechanical modelling constitutes a methodological framework applicable to a broader range of questions in combat sports biomechanics.

6. References

- Bartsch, A. J., Benzel, E. C., Miele, V. J., Morr, D. R., & Prakash, V. (2012). Boxing and mixed martial arts: preliminary traumatic neuromechanical injury risk analyses from laboratory impact dosage data. *Journal of neurosurgery*, 116(5), 1070–1080.
- Cross, R. (1999). The bounce of a ball. *American Journal of Physics*, 67(3), 222–227.
- Efron, B., & Tibshirani, R. J. (1993). *An introduction to the bootstrap*. Chapman and Hall/CRC.
- El Guma, F., Ali, A. Y., Eltaweel, M., Musa, R. A., & Shokeralla, A. A. (2026). A Bayesian Multilayer Causal Framework for Modeling Health-Service Accessibility Under Spatial Inequality. *Letters in biomathematics*, 13(1), 15–26.

- Harris, C. R., Millman, K. J., Van Der Walt, S. J., Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., & Smith, N. J. (2020). Array programming with NumPy. *Nature*, 585(7825), 357-362.
- Loturco, I., Nakamura, F. Y., Artioli, G. G., Kobal, R., Kitamura, K., Abad, C. C. C., Cruz, I. F., Romano, F., Pereira, L. A., & Franchini, E. (2016). Strength and power qualities are highly associated with punching impact in elite amateur boxers. *The Journal of Strength & Conditioning Research*, 30(1), 109-116.
- McKinney, W. (2010). Data Structures for Statistical Computing in Python. In *Proceedings of the Python in Science Conference* (Vol. 445, pp. 56-61). SciPy.
- Mooney, C. Z. (1997). *Monte carlo simulation*. Sage.
- Pierce, J. D., Reinbold, K. A., Lyngard, B. C., Goldman, R. J., & Pastore, C. M. (2006). Direct Measurement of Punch Force During Six Professional Boxing Matches. *Journal of quantitative analysis in sports*, 2(2), 1-19.
- Piorkowski, B. A., Lees, A., & Barton, G. J. (2011). Single maximal versus combination punch kinematics. *Sports biomechanics*, 10(01), 1-11.
- Smith, M., Dyson, R., Hale, T., & Janaway, L. (2000). Development of a boxing dynamometer and its punch force discrimination efficacy. *Journal of sports sciences*, 18(6), 445-450.
- Viano, D. C., Casson, I. R., Pellman, E. J., Bir, C. A., Zhang, L., Sherman, D. C., & Boitano, M. A. (2005). Concussion in professional football: comparison with boxing head impacts—part 10. *Neurosurgery*, 57(6), 1154-1172.
- Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., & Bright, J. (2020). SciPy 1.0: fundamental algorithms for scientific computing in Python. *Nature methods*, 17(3), 261-272.
- Walilko, T. J., Viano, D. C., & Bir, C. A. (2005). Biomechanics of the head for Olympic boxer punches to the face. *British journal of sports medicine*, 39(10), 710-719.
- Winter, D. A. (2009). *Biomechanics and Motor Control of Human Movement*. John Wiley & Sons.
- Wu, G., Van der Helm, F. C., Veeger, H. D., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A. R., McQuade, K., & Wang, X. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. *Journal of Biomechanics*, 38(5), 981-992.