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Direct Measurement of Punch Force During Six Professional Boxing Matches

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Abstract

Despite considerable research into boxing, surprisingly little is known concerning the fundamental physics of forces delivered in a boxing match. Most previous punch force estimates have been obtained from laboratory studies in which an experienced boxer struck an inanimate object. This paper presents the first direct measurement of punch force in professional boxing matches. Measurements were made using a proprietary system that records the force associated with punch impact. Twelve boxers wore boxing gloves incorporating the *bestshot* System ^{TM} in six professional boxing matches across five different weight classes. The force of each delivered punch was measured across all rounds of all bouts. Mean punch forces delivered ranged from 866.6 N (Super Middleweight) to 1149.2 N (Light Middleweight) across the fights and was not significantly correlated with boxer's weight. In each of the three bouts where the outcome was determined by judges' decision, the boxer delivering the greater cumulative force and the greater number of punches won unanimously. These measurements, the first direct measurement of punch force in professional boxing matches, are considerably less than those found in laboratory demonstrations, and likely reflect the dynamic nature of the ring. The ability to measure punch force directly may be beneficial in training, judging, and monitoring the health of boxers during competitive matches.

KEYWORDS: punch force, boxing, force measurement, boxing physiology

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Introduction

The sport of boxing has historical roots to Sumeria of 5000 BC and the early Olympic Games dating to 688 BC (Seltzer, 2000). Boxing has been an established recognized sport in the United States and Europe since the late 1700s, and remains a popular sporting event at both amateur and professional levels (Seltzer, 2000). The vigor and stamina demands of this taxing sport are considerable, and the successful boxer is an individual who possesses exceptional speed, strength, and agility (Smith et al., 2000). Although substantial research has been conducted into the biomechanics of boxing and the injury potential (Goldsmith, 2001; Haglund and Eriksson, 1993; Heilbronner et al., 1991; Zhang et al., 2003), surprisingly little is known concerning the fundamental physics of punch forces in a boxing match. This paper presents the first direct measurement of the force delivered by punches landed in professional boxing matches.

Previous attempts to measure the force of a delivered punch have focused on boxers punching an inanimate object outside the confines of the boxing ring. Earlier attempts used diverse mechanical targets such as water-filled punch bags (Fritsche, 1978; Joch et al., 1981; Fortin, unpublished manuscript), accelerometers contained within conventional punching bags (Baagrev and Trachimovitch, 1981), and padded metal targets suspended as a ballistic pendulum (Atha et al., 1985). Estimates derived from these mechanical systems varied as a function of weight class and boxing status (amateur versus professional), and ranged from 2,697 Newtons (N; one Newton equals 0.224809 lb.) for a heavyweight amateur boxer (Karpilowski et al., 1994) to 4,096 N for a heavyweight professional boxer (Atha et al., 1985). Atha et al. (1985), based on comparison measurements with submaximal punches, estimated that the maximal force that could be delivered to a human's head was 6,320 N.

In more recent work, Smith et al. (2000) developed a boxing dynamometer to measure the force of simulated straight punches delivered by elite, intermediate, and novice boxers to a boxing manikin permanently fixed to a mounting plate. Measurements were calibrated using a simulated straight jab and revealed substantial punch force differences in boxing class (elite, intermediate, and novice) and hand (lead or "jab" hand versus rear or "punch" hand). Thus, elite boxers punched with a mean maximal force of 2,847 N for the lead hand and 4,800 N for the rear hand. Intermediate (Lead: 2,283 N; Rear: 3,722 N) and novice (Lead: 1,604 N; Rear: 2,381 N) boxers delivered significantly less force per punch compared to the elites. These data represent the currently available best estimates of punch force, albeit in a controlled laboratory setting.

Whereas these measures provide accurate estimates of the maximal *potential* force that can be delivered by a human punch, they likely overestimate the *actual* force delivered in a boxing match. There are obvious dramatic differences between punching an inanimate target and a moving target who can defend himself or herself. In the ring, the target is a fellow athlete who can avoid a punch completely, partially evade a punch to reduce the force of impact, block or deflect the punch to a less critical target, or receive the punch before optimum reach, and therefore maximal punch force, is obtained. Further, the threat of a counterpunch may prevent a boxer from being able to prepare and deliver a maximal force punch. Thus, the dynamics of the ring reflect a substantially harder task than that of a laboratory simulation: to strike a moving target who can strike back. For these reasons, existing measures of punch force may not reflect the realities of the ring. Instead, a more accurate assessment would entail a system capable of measuring actual punch force in the context of a live boxing match. The present paper describes the results of such a system.

The *bestshot* System™ a proprietary system created by SensorPad Systems, Inc. (SPS; Norristown, PA), was developed to measure punch force in boxers. This system uses a lightweight, flexible force sensor embedded in the scoring section of the glove (the portion covering the knuckles in a clenched position) to record punch force upon contact. The present study describes the results of the use of this system in six competitive boxing matches across five different weight classifications. These data represent the first known measurements of the actual force of punches delivered in the ring.

Method

Participants. Twelve boxers wore boxing gloves incorporating the *bestshot* force measurement system in six professional boxing matches held between January, 2003, and November, 2004, at the Legendary Blue Horizon in Philadelphia, PA. Fights were selected to represent a range of weight classifications from Junior Lightweight to Heavyweight. Table 1 contains the relevant fight information for each bout, and is arranged by weight class in ascending order. All participants and their respective trainers were fully informed of the use of the force measurement system and provided informed consent to the use of the gloves.

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Table 1. *Fight Information and Boxer Demographics for Six Professional Boxing Matches Using the Bestshot Force Measurement System*

Date	Weight Classification	Boxer	Age	Weight (kg.)	Record (W-L-D)
1/31/2003	Junior Lightweight	1	27	59.0	2-0-0
		2	24	61.7	0-0-0
10/8/2004	Light Welterweight	3	18	61.7	6-1-1
		4	28	62.3	2-1-0
11/5/2004	Light Welterweight	5	27	66.9	12-9-1
		6	36	66.1	7-1-2
11/5/2004	Super Middleweight	7	25	75.7	7-0-1
		8	38	75.3	5-4-3
10/8/2004	Cruiserweight	9	22	82.0	3-2-1
		10	20	80.5	1-0-0
1/31/2003	Heavyweight	11	32	99.8	3-2-2
		12	31	98.9	26-20-3

Equipment and Materials. The *bestshot* System, a proprietary system created by SPS, was used to measure punch force during the six monitored matches. The system records the force associated with impact and communicates that information to a remote receiver (Figure 1). This system uses a lightweight, flexible force sensor embedded in the area of the glove adjacent to the hitting area of the fist to record punch force upon contact. The sensor is a single element, multiplayer, capacitive force sensor originally designed and patented for use in an isometric knee device to measure muscle torque in osteoarthritis patients (U.S. Patent No. 5,449,002 [1995], Goldman et al., 2003). The sensor has an effective impact measurement area of approximately 120 cm^2 that is incorporated into the foam padding of the glove. Any force experienced on the effective measuring surface of the glove is transferred to the force sensor.

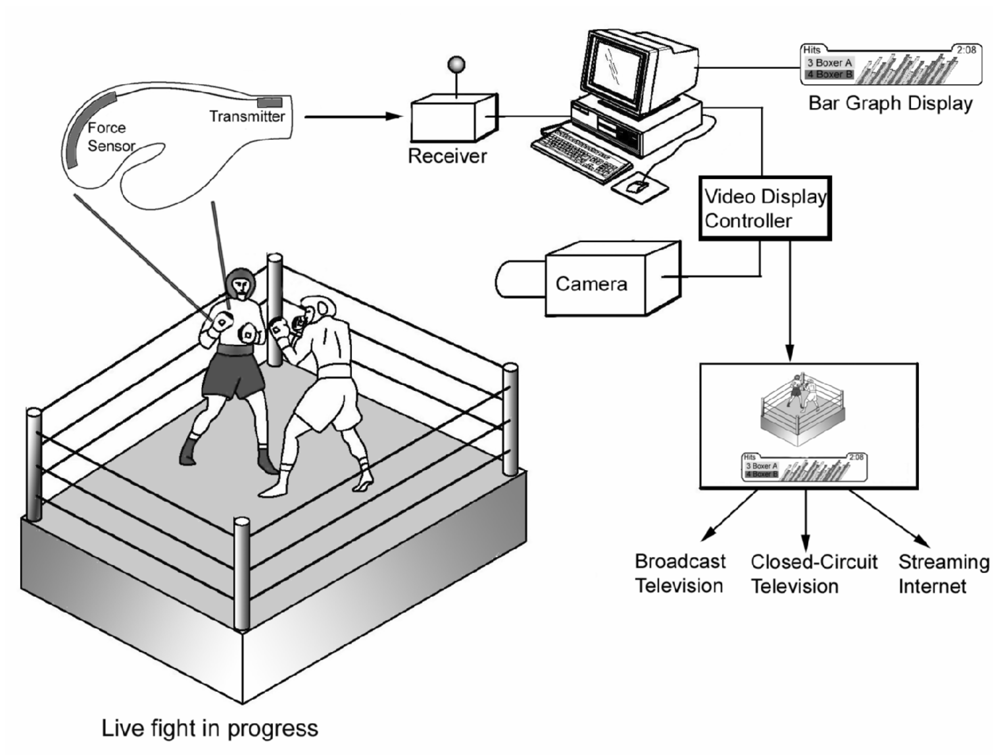

Figure 1. A diagram of the *bestshot* System^{TM} for measuring punch force impact.

The sensor is connected to a compact electronics unit in the wrist region of the glove. This unit receives the signal from the sensor and, in turn, transmits punch information to a receiver outside the ring via radio frequency telemetry. The information that is measured and conveyed by the system includes glove identification, maximal force of the punch, and punch duration. This information is sent to the receiver via burst transmission of a data packet. Transmission protocols incorporate algorithms to prevent data packet collision from multiple gloves. Additionally, each individual impact is associated with a sequence number that increments by one with successive punches. This hit sequence number is used to flag missed data packets. The lower limit of force recorded by the system is set at 500 N. Contact below this standard is considered to be incidental contact or “pity-pats”, and, thus, not recorded by the system.

The receiver, which has a range of over 35 m, is connected to a PC-type computer that stores all information. The computer also provides an instant visual bar graph depiction of punch force in real-time that can be overlaid on a video signal to be viewed on closed-circuit television, streaming video on the Internet, or broadcast television. In calibration tests, reception of transmitted data packets

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was 98% or better with the receiver at ringside. (SPS unpublished data).

Calibration of the glove was performed using a drop platform apparatus developed by ARCCA Incorporated of Penns Park, PA, an engineering firm that specializes in impact tests, such as automobile crash investigations. The apparatus consisted of a wooden platform attached to an overhead pulley with the platform straddling two vertical cables. Bolted on the floor directly under the center of the platform was a load cell accurate to 5,000 lbs (2268.0 kg). On this load cell was attached a machined wooden two-by-four on which a boxing glove could be mounted in the vertical position (i.e., fist pointed upwards). The platform was repeatedly lifted and then dropped from various heights to create impacts of known forces as measured by the load cell. For testing of the gloves, the 8-pound padded platform was dropped from various heights onto 8- and 10-ounce Everlast Pro-Fight gloves (the two most common weights of professional boxing gloves) modified to include the force measurement system. The peak force observed by the load cell and the force value transmitted by the glove (an 8-bit value) were simultaneously recorded for numerous drops at varying heights.

Plotting the glove-measured force values against the load cell generated force values in units of pounds displayed a characteristic force curve. The data were fit to both 2nd and 3rd order equations with the 3rd order equation having a better fit as expected. Error was determined by calculating the average of the differences between the measured and calculated force values divided by the measured force value. For the 3rd order calibration curve the average error for the 8-ounce glove was 4.0%. The 8 and 10-ounce gloves had nearly identical calibration curves, an expected finding as the foam at the fist is the same for either 8- or 10-ounce gloves.

The gloves used in the analyzed bouts were modified Everlast 1008 8-ounce and 1010 10-ounce Pro-Fight boxing gloves. The glove was modified to incorporate the SPS sensor and miniaturized electronics. The electronics unit and battery were embedded in the wrist region of the glove. The entire system (sensor, wires, electronics, and battery) adds 36 grams (1.27 oz.) to the overall mass of the glove. Laboratory evaluation of the balance, velocity calculations, impact response (theoretical and experimental), and hardness of the glove determined that there was no perceptible difference between a modified glove and a regular unmodified glove (Pastore, 2003). After the matches, the boxers all indicated that they felt no difference between the modified gloves and standard Everlast gloves when either punching or being hit.

Protocols. Permission to use the *bestshot* System™ was obtained from the Pennsylvania State Athletic Commission, the owners of the Legendary Blue Horizon, the boxers, and their managers. The system was used during six professional boxing matches held in the boxing ring of the Legendary Blue

Horizon in front of a crowd for each fight. For all fights, the receiver was placed 10 m from ringside and connected to the computer, which recorded all information. Each fight was professionally refereed and judged.

The telemetry system was calibrated and tested prior to the start of each fight. Following calibration and testing, each boxer was given the modified boxing gloves to wear during the scheduled boxing matches. The system was on continuously for the duration of the bouts, and the receiver was monitored by a SPS representative throughout the evening. Fights were otherwise conducted in the normal manner for each boxing venue.

Descriptive statistics, correlations, and multiple regression analysis were calculated using SPSS Version 13 for Windows.

Results

Four of the six fights lasted the scheduled duration of 6 rounds for the Heavyweight bouts and 4 rounds for the other fights. One Light Welterweight fight was discontinued when Boxer 4 suffered a hand injury in the first round that left him unable to continue. The Super Middleweight fight similarly ended after the first round due to an accidental head butt delivered to Boxer 8.

Table 2 provides mean punch force in Newtons, the number of hits, maximal punch force, and the total force delivered by each boxer in the six professional boxing matches. A total of 1675 punches were measured over the six bouts, ranging from a minimum of 32 punches thrown in the one-round Super Middleweight match to a maximum of 500 punches in the four-round Light Welterweight match. Mean punch forces ranged from 866.6 N (Super Middleweight) to 1149.2 N (Light Middleweight) across the fights. Perhaps surprisingly, mean punch force delivered across the different fights was not significantly correlated with boxer's weight ($r = 0.22$, $p = 0.50$). The greatest mean punch forces observed were by a Light Middleweight (1149.2 N) and a Light Welterweight (1124.3 N). Conversely, the lowest mean punch forces were by a Super Middleweight at 866.6 N and a Cruiserweight at 920.5 N.

Cumulative punch forces similarly showed no relationship with boxer weight. Rather, cumulative punch forces, a function of punch force, number of punches delivered, and the number of rounds, were highest in the 4-round Light Middleweight fight (342472 N delivered by Boxer 5) and the 6-round Heavyweight fight (329524 N delivered by Boxer 11). Cumulative punch force did, however, appear to play a role in the outcome of the fight. In each of the three bouts where the outcome was determined by judges' decision, the boxer delivering the greater cumulative force and the greater number of punches won unanimously.

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Table 2. *Direct Measures of Punch Force in Newtons and Number of Hits by Boxer for Six Professional Boxing Matches*

Weight Classification	Rounds	Boxer	Mean Punch Force (s.d.)	Total Force Delivered [No. Hits]	Maximal Punch Force	Result
Junior Lightweight	4	1	935.1 (395.2)	149611 [160]	2558	W: UD
		2	1092.6 (551.5)	73204 [67]	3554	
Light Welterweight	1	3	974.4 (469.0)	50668 [52]	2283	W: TKO
		4	1124.3 (597.7)	78703 [70]	3702	
Light Welterweight	4	5	1149.2 (665.8)	342472 [298]	5033	Draw
		6	932.1 (465.1)	188280 [202]	3702	
Super Middleweight	1	7	1012.4 (402.2)	20248 [20]	1722	ND
		8	866.6 (317.9)	10400 [12]	1571	
Cruiserweight	4	9	1035.1 (581.5)	140776 [136]	3631	
		10	920.5 (508.5)	197909 [215]	5358	W: UD
Heavyweight	6	11	1113.3 (569.4)	329524 [296]	3554	W: UD
		12	1108.3 (471.5)	162916 [147]	2869	

Note. The Light Welterweight fight between Boxers 3 and 4 was stopped after 1 round when Boxer 4 suffered a hand injury that prevented him from continuing. The Super Middleweight fight between Boxers 7 and 8 was stopped after 1 round due to an accidental head butt delivered to Boxer 8.
Abbreviations: W for Winner, UD for Unanimous Decision, TKO for Technical Knockout, ND for No Decision.

A multiple regression analysis confirmed the lack of a significant relationship between mean punch force and boxer weight. For this analysis, mean punch force was used as the dependent variable and the potential predictors used were boxer weight, boxing experience (as measured by the number of professional bouts), boxing success (as measured by winning percentage of prior bouts), and the number of hits in the current bout. None of the independent variables was a significant predictor of mean punch force in this analysis (boxer weight [$t = 0.21$, $p = 0.84$]; boxing experience [$t = 0.50$, $p = 0.63$]; boxing success [$t = -0.78$, $p = 0.46$], and number of hits [$t = 0.70$, $p = 0.51$]).

The majority of punches were delivered at forces substantially lower than laboratory predictions. Of the 1675 punches delivered across the six bouts, 59.2% were delivered below 1000 N. Only 89 of the punches (5.3%) were delivered above 2000 N, and only 18 punches (1.1%) were delivered above 3000 N. Of the three punches over 4000 N, two were delivered by a Light Welterweight (4179 N and 5033 N by Boxer 5) and one was delivered by a Cruiserweight (5358 N by Boxer 10). By contrast, the most forceful Heavyweight punch was delivered at 3554 N. Maximal punch force for each boxer is listed in Table 2.

Two fights at the weight extremes (Junior Lightweight and Heavyweight) were selected for further analysis. One fight was the junior lightweight four-round match between Boxers 1 and 2. The second fight was a heavyweight six-round contest between Boxers 11 and 12. Three of the four boxers were right-handed; Boxer 11 was left-handed.

Table 3 lists the mean punch force by hand for each round by the junior lightweight boxers. The mean punch force for all punches in this bout was 1,003.2 N (s.d. = 408.9) for the lead (jab) hand and 964.2 N (s.d. = 483.9) for the rear (power) hand. The force delivered did not differ significantly for lead versus rear hand (t [225] = 0.65, $p = 0.52$). Boxer 2 delivered significantly more force per punch than did Boxer 1 (1,092.6 N versus 935.1 N; t [225] = 2.42, $p = 0.016$), but threw far fewer punches (67 versus 160). Thus, over the course of the bout, Boxer 1 successfully delivered a cumulative total of 149,611 N whereas Boxer 2 delivered less than half of this amount (73,204 N). Boxer 1 won the fight by unanimous decision. Cumulative force delivered did not differ significantly across rounds (F [3, 223] = 2.09, $p = 0.10$). However, there was a significant difference in punch force for punches delivered in the last round (1,097.6 N) compared to the first round (898.3 N; t [123] = 2.30; $p = 0.023$).

Table 4 provides a frequency count by punch force for the junior lightweight boxers. These data show that most punches were delivered with low punch force. Almost two-thirds (64.3%) of punches were delivered at or below 1,000 N, and 87.7% of all punches were below 1,500 N. Only 2 of 101 punches landed with the lead hand, and only 5 of 126 punches landed with the rear hand, were delivered with a force of 2,000 N or greater.

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Table 3. *Direct Measures of Punch Force in Newtons and Number of Hits by Round for Two Junior Lightweight Boxers in a Professional Boxing Match*

Force	Boxer 1		Boxer 2	
	Lead Hand	Rear Hand	Lead Hand	Rear Hand
	Round 1			
Mean (s.d.)	999.1 (287.9)	762.9 (294.8)	932.4 (347.1)	1263.3 (958.1)
Maximal	1570.2	2072.9	1757.1	3554.1
Total	9990.7	26702.7	12121.4	11369.7
No. Hits	10	35	13	9
	Round 2			
Mean (s.d.)	934.8 (413.7)	993.1 (431.9)	951.9 (377.4)	974.2 (0.0)
Maximal	1988.4	1721.5	1681.4	974.2
Total	12152.5	15889.1	7615.4	1948.3
No. Hits	13	16	8	2
	Round 3			
Mean (s.d.)	827.0 (231.7)	926.3 (311.5)	1110.7 (407.5)	1596.9 (802.9)
Maximal	1338.91	1605.8	1872.7	2606.7
Total	18193.2	24082.7	11107.2	7984.6
No. Hits	22	26	10	5
	Round 4			
Mean (s.d.)	1301.3 (587.3)	1003.6 (446.5)	1062.2 (436.6)	1043.6 (517.4)
Maximal	2557.7	2152.9	1832.7	2197.4
Total	19518.8	23081.8	10622.4	10435.5
No. Hits	15	23	10	10

Table 4. *Frequency count by punch force for Two Junior Lightweight Boxers and Two Heavyweight Boxers in Professional Boxing Matches*

	Junior Lightweight Boxers		Heavyweight Boxers	
Force Range (N)	No. of Punches	% of Total	No. of Punches	% of Total
3500-400N	1	0.4	1	0.2
3000-3499N	0	0.0	3	0.7
2500-2999N	2	0.9	4	0.9
2000-2499N	4	1.8	19	4.3
1500-1999N	21	9.2	63	14.2
1000-1499N	53	23.4	130	29.4
500-999N	146	64.3	223	50.3
TOTAL	227	100.0	443	100.0

Table 5 lists the mean punch force by hand for each round by the heavyweight boxers. The mean punch force for all punches in this bout was 1,125.0 N (s.d. = 506.4) for the lead hand and 1,098.1 N (s.d. = 569.5) for the rear hand. The force delivered did not differ significantly for lead versus rear hand (t [441] = 0.52, p = 0.60), nor was there a significant difference in the force per punch delivered by each boxer (Boxer 11: 1,113.3 N; Boxer 12: 1,108.3 N; t [441] = 0.09. p = 0.93). Boxer 11 delivered almost twice as many punches as did Boxer 12 (296 versus 147), and thus, far greater cumulative force (329,524 N versus 162,916 N). As with the junior lightweights, the boxer delivering the greater cumulative force (Boxer 11) won the bout by unanimous decision. Cumulative force delivered did not differ significantly across rounds (F [5, 437] = 0.34, p = 0.89), and there was no significant difference in punch force for punches delivered in the first round (1,180.5 N) compared to the final round (1,073.5 N; t [125] = 1.00; p = 0.32).

Frequency counts by punch force for the heavyweight boxers are located in Table 4. For the lead hand, the majority of punches (50.3%) were delivered with a force below 1,000 N, and 79.7% of punches were below 1,500 N. Of 222 punches landed with the lead hand, only 12 delivered a punch force of 2,000 N or greater. Rear hand punches most often delivered a punch force of under 1,000 N, and only 15 of 221 punches delivered a punch force of 2,000 N or greater.

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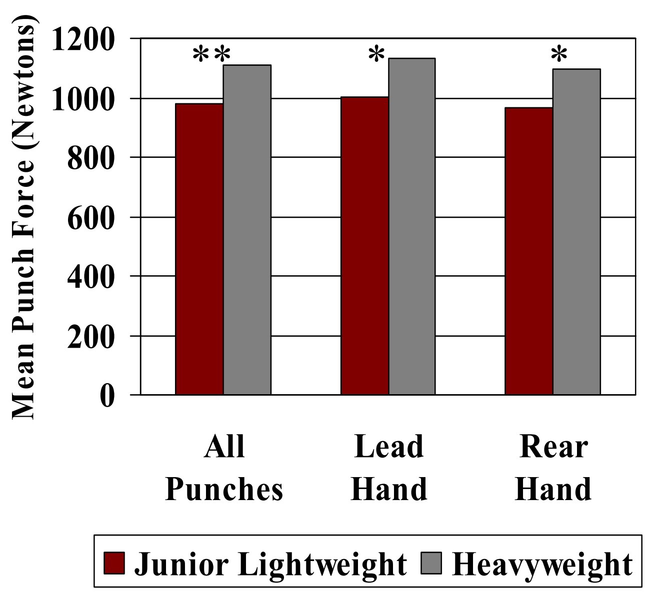
Table 5. *Direct Measures of Punch Force and Number of Hits by Round for Two Heavyweight Boxers in a Professional Boxing Match*

Force	Boxer 11		Boxer 12	
	Lead Hand	Rear Hand	Lead Hand	Rear Hand
	Round 1			
Mean (s.d.)	1304.8 (770.2)	1109.6 (367.7)	845.2 (---)	1044.5 (693.8)
Maximal	2762.4	1570.2	845.2	2869.1
Total	27401.1	12205.9	845.2	11489.8
No. Hits	21	11	1	11
	Round 2			
Mean (s.d.)	1137.5 (580.4)	1232.6 (490.4)	1100.7 (658.3)	999.2 (406.3)
Maximal	3038.1	2072.9	2415.4	1721.5
Total	40950.3	24652.1	9906.2	20982.3
No. Hits	36	20	9	21
	Round 3			
Mean (s.d.)	1044.0 (402.1)	1216.4 (886.9)	1203.8 (613.4)	1162.1 (379.6)
Maximal	1872.7	3554.1	2326.4	1952.8
Total	27143.1	18246.6	9630.4	29051.3
No. Hits	26	15	8	25
	Round 4			
Mean (s.d.)	1043.6 (522.3)	1043.8 (406.5)	1383.4 (428.4)	1247.0 (469.3)
Maximal	2655.6	2112.9	1952.8	2326.4
Total	43832.8	25052.4	6917.0	28682.1
No. Hits	42	24	5	23
	Round 5			
Mean (s.d.)	1105.8 (619.2)	1105.6 (595.5)	658.3 (---)	996.1 (449.0)
Maximal	3100.4	2415.4	658.3	1797.1
Total	29856.5	19901.4	658.3	15938.0
No. Hits	27	18	1	16
	Round 6			
Mean (s.d.)	1023.4 (581.9)	1188.4 (564.8)	951.3 (378.4)	1107.8 (423.5)
Maximal	3416.2	2326.4	1681.4	2237.5
Total	38890.8	21391.5	6659.0	22156.6
No. Hits	38	18	7	20

Figure 2 displays mean punch force by hand for each weight class. The heavyweight boxers delivered significantly more force per punch compared to the junior lightweight boxers (t [668] = 3.12, p = 0.002). This relationship was observed for punches with both the lead hand (t [321] = 2.12, p = 0.035) and the rear hand (t [345] = 2.22, p = 0.027). The heavyweight boxers, compared to the junior lightweight boxers, also threw more punches per round (73.8 combined versus 56.8 combined). Thus, overall, heavyweight boxers each delivered more cumulative force per round (82,073.3 N) compared to the junior lightweight boxers (55,704.0 N).



***   p < 0.05**
**** p < 0.001**

Figure 2. Mean punch force by hand for each weight class.

Discussion

Whiting et al. (1988), in their comprehensive kinematic analysis of thrown punches, noted the many factors associated with the overall impact of a punch; including punch velocity, location and orientation of impact, the number of punches sustained, and punch force. Of these parameters, determination of punch force has been the most elusive. The data in the present study represent the first

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direct measurements of punch force in professional boxing matches, and, thus, contribute a critical parameter to this comprehensive model of the power of a punch. Mean punch forces in six professional bouts ranged from 866.6 N to 1149.2 N and did not significantly correlate with boxer weight. In each bout where outcome was determined by the judges, the boxer delivering the greater cumulative force won by unanimous decision.

These direct measures of actual punch force are substantially less than punch force measures previously derived from experimental work in which an experienced boxer struck an inanimate, non-moving object (Atha et al., 1985; Smith et al., 2000). In the experimental work, the boxer had unlimited time to get into position and deliver the punch without concern of a retaliatory punch. Thus, whereas these designs have provided accurate estimates of the maximal *potential* force, they appear to considerably overestimate the actual forces delivered in the ring. The mean punch force for the hardest-hitting heavyweight boxers observed in the present study was less than one-fourth (23.2%) of the mean maximal rear hand punch force observed for elite boxers in the experimental demonstrations of Smith et al. (2000) and 27.1% of the estimate derived from Atha et al. (1985). Even the hardest punch landed in a heavyweight match (at 3,554.1 N) was considerably less than the mean rear hand force delivered by Smith et al.'s elite boxers and slightly over one-half (56.2%) of Atha et al.'s estimation of the maximal force that could be delivered to a human's head (6,320 N).

What these data illustrate is the importance of factors other than *potential* punch force in determining *actual* force delivered and received. Size and musculature may determine the force that can be delivered, but proper techniques of delivery and defense likely determine the force that is received. Experienced boxers, with knowledge of proper stance, hand position, and defense techniques (bobbing and weaving, slips, step backs, sidesteps, etc.), can avoid completely or substantially reduce the force that is received. For example, Atha et al. (1985) noted the rapidity with which a punch can be delivered. Their estimated time from the start of a punch to impact was measured at 100 ms, and these researchers noted that chances of evading such a blow after initiation of the punch were "slim". Evasion, therefore, must start before the onset of the punch. Successful evasion depends upon the boxer's ability to anticipate punches, so that as an opponent gets set to punch, the experienced boxer is already stepping back or sidestepping in defense. Similarly, constant movement around the opponent prevents the presentation of a stationary target and aids the successful boxer in avoiding punishing blows. Techniques such as these most likely reflect the discrepancy between the earlier experimental data and the present findings.

In this context, it is interesting to note that the two strongest punches delivered were in non-heavyweight bouts. Light Welterweight Boxer 4 delivered a punch at 5033 N in Round 2, and Cruiserweight Boxer 10 delivered a punch at

5358 N in Round 4. Each of these punches far exceeded the force of the hardest punch measured in either of the heavyweight bouts (3,554.1 N). That a 62.3 kg boxer and a 80.5 kg boxer delivered maximal punch forces in professional bouts greater than those delivered by heavyweights provides a strong suggestion that punch velocity (Whiting et al., 1988) and technique are as important in determining punch force as are size and musculature. An analogy might be made to the act of hitting a baseball in which batted distance is a function of bat velocity and technique, more so than the overall size of the batter (Adair, 1994).

The force delivered was consistent across all rounds for junior lightweights and heavyweights, with the exception of a significant increase in force for punches landed in the last round of the junior lightweight bout. The fact that boxers can maintain sufficient velocity over the course of 200+ punches may be a testament to the conditioning and strength of these athletes. Further testing in bouts that extend the 12 rounds typical of professional matches is necessary to determine the role of fatigue in lessening punch force.

The present study demonstrates the ability and feasibility of measuring punch force directly in a live boxing match. The ability to do so offers several potential benefits for training, judging, and monitoring boxers. The ability to monitor forces delivered and received could provide a valuable tool in the training of boxers at both amateur and professional levels. The ability to measure punch force directly yields an effective means for measuring punch effectiveness and can be used to establish standards by which punch force can be assessed and compared along a common unit of measurement (punching pounds of force). Such standards could aid trainers in identifying strengths and weaknesses of technique and areas necessary for improvement. In judging, established standards can provide an objective measure of punch force to complement existing judging criteria.

Measuring punch force has potential safety benefits for boxers as well, as it may be used to address the long-term question of health issues related to boxing. Justifiable concerns of long-term cognitive disorders arising in career boxers have been raised (Goldsmith, 2001; Haglund and Eriksson, 1993; Heilbronner et al., 1991; Zhang et al., 2003), and professional boxing has had several well-publicized fatalities resulting from damage sustained in the ring. Whereas grave consequences may result from a single punch thrown with considerable force, much research has focused on the cumulative force received across multiple bouts (Haglund and Erikkson, 1993; Ravdin et al., 2003). Boxing at both the amateur and professional level has responded by greatly increased safety monitoring of boxers in the ring by a ringside physician and between bouts through the use of neurological and neuropsychological testing (Ryan, 1998; Sheldon, 1998), resulting in a substantial decrease in the number of fatalities in the ring (Sheldon, 1998). Widespread use of a punch force measurement system

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would provide a valuable monitoring device at ringside. Through actively monitoring of the forces delivered to a boxer, it may be possible to minimize severe damage induced by the cumulative effect of punches. Such a system could provide an immediate warning of a single punch delivered at the extreme end of potential punch force. Measures of cumulative force could be used as medically-justified grounds to terminate a fight by technical knockouts (TKOs), for example, or a referee may use force data in guiding the decision to allow a fight to continue.

In that respect, it is worth noting that the *bestshot* punch force measurement system used in the present study does not transmit information regarding the point of contact. Thus, the total maximal force delivered per boxer should be viewed with considerable caution, as an undetermined portion of these totals involved contacts delivered to the body, arms, and even gloves of the opponent. Determining the total force delivered to the head and neck region would entail videotape analysis of bouts using the force measurement system to identify the punches and their associated forces delivered to each region. Work is currently underway to identify the locations of delivered punches as a follow-up project to the current study. In addition, further work with multiple bouts across all weight classifications can extend the present findings in documenting the power of the punch.

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