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An Examination of the Biomechanics of the Cross, Hook and Uppercut between Two Elite Boxing Groups †

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Abstract: In boxing, an efficient punch requires a combination of force, velocity and stability of the athlete. Being able to monitor these parameters has the potential to better inform training practices required to reach high performance. Hence, the aim of this study was to investigate the differences in punching execution between two groups of elite boxers (senior vs. junior) using three biomechanical indicators of performance in boxing. Each athlete was equipped with an instrumented suit composed of 17 inertial measurement units (IMU) and were asked to perform several series of punches with 3 standardized punching techniques (cross, hook and uppercut) on a punching bag with maximal force. Linear velocity, stability and punch forces were computed from the different sensors. Our findings show that senior boxers systematically produced more force and at a higher velocity for the three punching techniques compared to juniors. The IMU analysis also reveals differences of joint contributions between seniors and juniors, juniors presenting a higher contribution of the shoulder for the three punching techniques.

Keywords: punch; inertial measurement unit; biomechanics; performance; efficiency

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1. Introduction

Boxing is a physically demanding combat sport. Boxers rely on a combination of strength, coordination, speed, and stamina to succeed in impacting the opponent while evading an adversary's punches [1,2]. A successful performance requires the ability to deliver precise punches above the belt, to the head or the torso, without being punched back. In amateur boxing, such as seen during the Olympic Games, boxers aim to score by striking the opponents during rounds of 3 min. As varying degrees of force and speed are required in boxing, athletes throw punches with their rear or front hand [3]. The rear hand (the furthest from the target) usually provides more punching force while maximal speed can be achieved with the front hand (the closest to the target) [4]. The defensive boxer is allowed to dodge punches with hand, trunk as well as feet actions. There are three main attacking techniques: the cross, hook and uppercut. The cross is a forward translation of the body whereas the two other punches involve an overall rotation of the body. Previous studies have reported an activity rate of ~1.55 actions/s, consisting of ~21 punches, ~3.6 defensive movements and ~56 vertical hip movements per-minute over three subsequent rounds lasting ~184 s for male elite athletes [5,6].

During the round, boxers aim to knock their opponent out, touching the optimal target zone in order to win the fight. As knockout is a constant goal during a match, boxers must increase punch impact and, as a consequence, knockout power [7,8]. Unlike professionals, amateur boxers tend to favor quick strikes over heavy blows [8]. Therefore, they need to develop maximal speed at the end of the distal segment of the kinematic chain. In this aspect, boxing generates the same type of segment interactions as sports involving throwing and kicking such as baseball, tennis, golf or rugby. Achieving high speed, and force, at the end of the distal segment is usually a result of a proximal-to-distal sequencing motion as the summation of speed principle states [9–11]. However, its computation remains a challenge [12]. The synchronization of the body segments' motion can highlight the differences in skills between athletes [9]. Hence, understanding these biomechanical differences can provide valuable insight for lower level athletes and coaching staff desiring to refine their training practices.

With this in mind, the aim of our study was twofold: (a) to identify biomechanical differences between senior elite boxers and junior elite boxers; and (b) to discriminate the biomechanical parameters responsible for performance in elite boxers.

2. Materials and Methods

2.1. Participants

Two groups of boxers volunteered to participate in this study: 15 senior elite potential Olympic medalist boxers (Senior) (mean age 21.1 ± 3.0 years; stature 1.79 ± 0.09 m; body mass 73.6 ± 17.9 kg) from the French National boxing academy and 8 junior elite boxers (Junior) (mean age 16.1 ± 0.7 years; stature 1.75 ± 0.05 m; body mass = 61.0 ± 9.3 kg) from a regional boxing academy. All the participants were injury-free at the time of data acquisition. This study was approved by the French Boxing Federation and carried out in accordance with the Declaration of Helsinki. All the participants were informed of the objectives and risks of the study and their parent or legal guardian signed an informed consent form before the study began.

2.2. Protocol

Before testing sessions, a standardized warm-up was organized under the supervision of the coach. The participants were asked to perform 3 punches using standardized techniques (cross, hook and uppercut) with, at first, their front hand, then, their rear hand, and finally, a combo: front hand immediately followed by rear hand. A series of 3 punches was executed for each technique. The instructions were to complete a precise motion in the direction of the punching bag with maximal possible strength. Participants wore a movement (MVN) Biomech Link suit (Xsens Technologies BV, Enschede, The Netherlands) collecting live kinematic data during the entire movement. This suit was composed of 17 miniature inertial measurement units (IMU) strapped onto the body. Each IMU contained a 3D gyroscope, a 3D accelerometer, and a 3D magnetometer in an 18 g box (about the size of half a matchbox 3.5 × 2.5 × 0.8 cm). Each IMU captured the 6 degrees of freedom of the body segment to which it was fixed, in real time at a sampling frequency of 240 Hz.

2.3. Data Processing

Based on the linear velocity and acceleration of each segment computed from the IMU, a customized MatLab™ program (7.10.0, R2010a, Natick, MA, USA) calculated the estimate of the ground reaction force distribution and the punch force at impact. All biomechanical analyses were performed according to the De Leva anthropometrical model [13].

This study focused on three parameters: the linear velocity at impact accessed via the hand's IMU, the stability processed from the ground reaction force distribution and the punching force at impact. The determination of stability and punching force is detailed below.

2.3.1. Stability Computation

Stability was computed from the estimation of the vertical ground reaction force (GRF) by the projection of the center of mass, as proposed in Equation (1).

$$\overrightarrow{GRF} = m(\overrightarrow{a_{CMz}} - \overrightarrow{g}) \quad (1)$$

In this equation, based on Newton's second law, $\overrightarrow{GRF}$ corresponds to the total ground reaction forces, m is the mass of the athlete, $\overrightarrow{a_{CMz}}$ is the vertical component of the center of mass acceleration obtained by the IMU, $\overrightarrow{g}$ corresponds to the gravitational acceleration.

In order to study the leg which is the most involved during the motion and to measure the athlete's balance during the motion, the GRF distribution between the right and left leg is computed based on a proportional distribution of the toes. First, the center of mass is calculated from the sum of the center of mass of each body segment and then projected onto the ground. Then the distance between the projected center of mass and the toes (respectively d_{CM-L} and d_{CM-R} for the left and the right foot) is measured with the kinematic data acquired by the IMU. d_{Total} corresponded to the distance between both feet (2). GRF distribution on the right foot ($\|\overrightarrow{GRF}\|_R$) and on the left foot ($\|\overrightarrow{GRF}\|_L$) was computed following the Equations (3) and (4) and was presented as a percentage of $\|\overrightarrow{GRF}\|$. GRF distribution of the front leg was used to estimate the boxer's stability: the athlete was the most stable when the GRF distribution of the front leg was close to 50%.

$$d_{Total} = d_{CM-L} + d_{CM-R} \quad (2)$$

$$\|\overrightarrow{GRF}\|_R = \frac{d_{CM-L} \times \|\overrightarrow{GRF}\|}{d_{Total}} \quad (3)$$

$$\|\overrightarrow{GRF}\|_L = \frac{d_{CM-R} \times \|\overrightarrow{GRF}\|}{d_{Total}} \quad (4)$$

2.3.2. Punching force Estimation

When computing the punching force, GRF was assumed constant between the moment preceding the impact and the impact. Thus, following the hypothesis that the lateral ground contact forces are negligible, it is possible to write Newton's second law before impact and at impact [14]. The punch force at impact $\vec{F}$ can be singled out and calculated: $\|\vec{F}\| + \quad \mathrm{ma} = \frac{\Delta \mathrm{P}}{\Delta \mathrm{t}}$ (5) where $\|\vec{F}\|$ is equivalent to the magnitude of the impact force of the punching bag on the boxer's hand, $\|\overrightarrow{GRF}\|_R$ and $\|\overrightarrow{GRF}\|_L$ match the ground reaction forces, m is the boxer's weight, P corresponds to the linear momentum of the boxer, t is the time frame, $\vec{g}$ is the gravitational acceleration and $\vec{a}$ is the acceleration of the center of mass of the boxer at the moment before impact.

2.3.3. Contribution of Body Segment Calculation

The contribution of body segments is computed by the analytic calculation of the velocity of the segment of interest. A kinematic chain is built from the reference point, in this case it is the pelvis, to the segment of interest [10]. The linear velocity of the kinematic chain is based on the linear velocity of the reference point. The segment angular velocity describes the other segments between the reference point and the segment of interest.

2.4. Statistical Analyses

Differences between groups (Senior vs. Junior) were analysed by independent t-tests. When the assumption of normal distribution was violated, a non-parametric Mann–Whitney U test was used. For all statistical analyses, a p value of 0.05 was considered to indicate significance. All data are presented as means ± standard deviations (SD), unless otherwise indicated.

3. Results

3.1. Punching Force and Speed

For all punching techniques, maximal force production was higher ($p < 0.01$) in Senior compared to Junior boxers (Figure 1A,B). The mean maximal force produced by Senior boxers was 3158 ± 1467, 2999 ± 1818 and 3242 ± 1767 N, while it was 1021 ± 449, 544 ± 235 and 700 ± 287 N for Junior boxers, for the cross, hook and uppercut, respectively. As displayed in Figure 1A, the results followed the same pattern between Senior and Junior boxers when force production is was considered relative to individual body mass (in N/kg). The punching speed was also higher ($p < 0.01$) in Senior compared to Junior boxers for the hook and uppercut only (Figure 1C). The mean Senior's maximal punching speed was 8.1 ± 2.1, 11.2 ± 2.0 and 10.2 ± 1.8 $m \cdot s^{-1}$ while it was 8.1 ± 1.3, 8.9 ± 0.9 and 7.3 ± 1.0 $m \cdot s^{-1}$ for Junior boxers, for the cross, hook and uppercut, respectively.

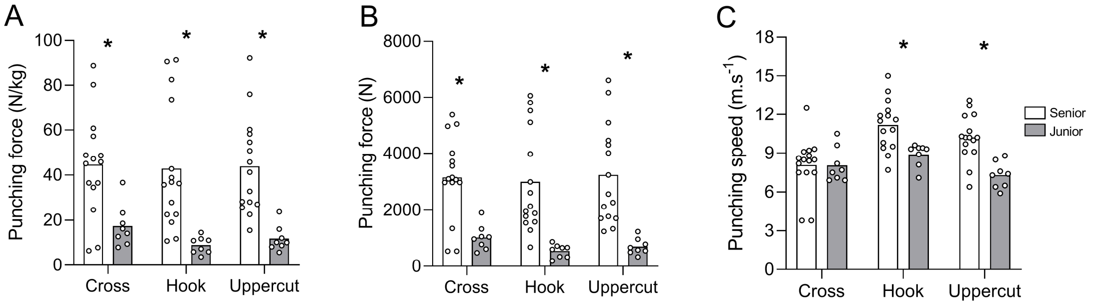

Figure 1. (**A**), punching force (N/kg), (**B**), punching force (N), (**C**), punching speed ($m \cdot s^{-1}$) for the different punching techniques for the two groups of boxers. Bars represent mean values while white points represent individual data points. * denotes a significant difference between groups ($p \leq 0.05$).

3.2. Technical Aspects of the Punch

The analysis of body segments' contributions showed different patterns between punches and between groups (Figure 2). In both groups, the elbow contributed the most to the punch during the cross (39.2% ± 35.9% and 27.1% ± 22.2% for Senior and Junior boxers, respectively), whereas it was the shoulder for the hook and uppercut. Additionally, the shoulder contribution was systematically higher in Junior compared to Senior boxers for the cross (29.1% ± 8.4% vs. 15.6 ± 12.5%, $p = 0.01$), hook (71.0% ± 12.3% vs. 50.1% ± 21.0%, $p = 0.01$) and uppercut (67.3% ± 11.9% vs. 54.8% ± 12.3%, $p = 0.02$). The trunk contribution was also higher in Junior compared to Senior boxers only for the cross (16.0% ± 10.6% vs. 6.7% ± 6.8%, $p = 0.01$). The pelvis contribution in the linear plane was higher ($p = 0.02$) in Senior (3.04% ± 4.2%) compared to Junior (−0.6% ± 1.5%) during the hook only.

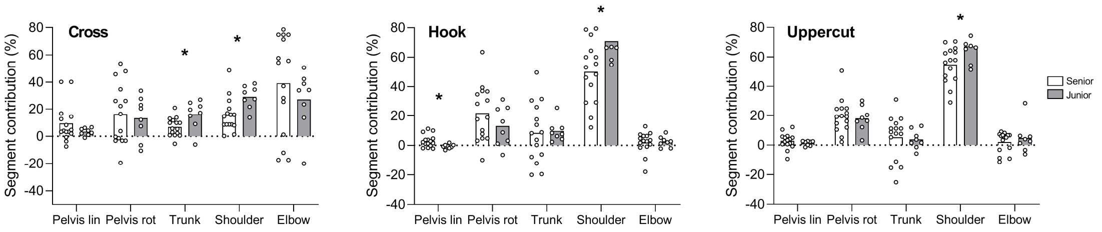

Figure 2. Segments' translation and rotation contributions (%) for the three punching techniques for the two groups of boxers. Segments' contributions for trunk, shoulder and elbow are a combined translation and rotation. Bars represent mean values while white points represent individual data points. * denotes a significant difference between groups ($p \leq 0.05$).

The 3D kinematic analysis also showed no difference in body positioning between groups for the three punching types, except for the head angle which was lower ($p = 0.01$) in Junior (19.8° ± 4.9°)

compared to Senior (24.0° ± 3.0°) during the cross. GRF shows an imbalance between the left and right foot only during the cross and in similar proportions between groups (mean ground reaction contributions between feet: 60.6% ± 24.9% vs. 39.4 ± 24.9% and 54.1% ± 7.1% vs. 45.9% ± 7.1% for the left vs. right foot in Senior and Junior boxers, respectively).

4. Discussion

Performance in boxing requires a combination of force and velocity of the acting arm, originating from an optimal synchronization of the different body segments. We examined the biomechanical patterns and resulting forces produced by senior vs. junior elite boxers for three punching types. Our main findings reveal differences in force, velocity, balance and segment contributions between groups, thus better informing on the conditions required to perform in boxing.

From the 3D kinematic analysis, we identified differences in motion patterns between the hook, uppercut and cross, across the groups of boxers. We find that in both groups, the elbow is the most active during the cross, while it is the shoulder for the hook and uppercut. The cross requires a straight trajectory with the elbow acting like a piston (flexion/extension) in a throwing movement in the sagittal plane and with very little rotation. The cross is considered as a short movement requiring the opening of the elbow to reach the target. In contrast, the hook and uppercut are longer and more complex. They require a circular trajectory in the sagittal plane with the shoulder predominantly mobilized to initiate a simultaneous rotation and translation of the arm. These differences of segment contributions observed in both groups between the cross and hook/uppercut show that the different punching techniques require very distinct biomechanical adjustments.

In both groups, force production was relatively similar between punching techniques, while the punching speed tended to be higher for the hook, which can be explained by the swinging nature of the movement. Not surprisingly, force production was higher in senior compared to junior boxers for the three different punches regardless of the body mass of the athletes [15]. The force values recorded for seniors (≥3000 N) are in accordance with values reported in the literature for elite boxers [16]. The punching speed was also higher for seniors compared to juniors, though only for the hook and uppercut. The distribution of GRF between the left and right foot was rather similar between groups with the front foot (indicated as left foot) systematically showing the highest values compared to the rear foot (indicated as right foot) in both groups. The balance between GRF for the right and left foot is important in boxing in order to facilitate energy transfer from the lower body to upper limbs, thus facilitating force production. Although only few studies have focused on this parameter, it is generally accepted that the greater the legs' contribution, the greater the punching force and this pattern is more prominent in experienced boxers [17]. An efficient boxer is typically characterized by a balanced foot grounding allowing throwing the fist through one synchronized movement of the scapula and upper body.

5. Conclusions

The aim of this study was to examine the biomechanical differences between elite senior and junior boxers in three different punching techniques. Nanotechnology inertial measurement units were positioned directly onto body segments to provide a full decomposition of the biomechanical variables associated with the boxing tasks. Results indicate differences in force, velocity, and body segment distributions between the two groups. These findings allow to highlight the best punching techniques, thus providing valuable information for practitioners and athletes to refine their training practices.

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