An innovative approach for real time determination of power and reaction time in a martial arts quasi-training environment using 3D motion capture and EMG measurements

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A Study Design
B Data Collection
C Statistical Analysis
D Manuscript Preparation
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Abstract

Background and Study Aim: Power and neural response are two fundamental elements in many martial arts striking. Currently, there are no practical methods exist to present these aspects to coaches and athletes in a training environment. This study introduced a new method for quantifying the two factors that could be used in real-time biofeedback training.

Material/Methods: The new method consisted of self-developed optical signal system, EMG measurement and 3D motion capture. The quantification was done by using kinematics of the punching bag and striking limbs analyzed with self-developed dynamic calculation programs. The setup was very close to a training environment with neglect-able influence on an athlete performance.

Results: The results showed that such quantification provided both total power and power components (i.e. linear & angular) of striking as well as the related response processes/time.

Conclusions: Since the method could offer feedback of power intensity, attack accuracy, central and peripheral reaction time to coachers and athletes, it would have great potential to become a biofeedback tool in practice for increasing training efficiency and effectiveness.

Key words: quantification • linear and angular power • attack accuracy • central and peripheral reaction time • real-time feedback

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Background and Study Aim

Two fundamental principles of striking in many martial arts are power and speed. Power, in the context of striking, can be thought of as the ability to deliver enough force to off balance, damage or knock out an opponent. Based on physics, power can be determined by the product of the force applied to an object and the object's change in velocity as a result of that force. Speed, in this instance, can be thought of as fast hand or foot movement and quick reaction.

These two themes permeate one of the most famous martial artists and arguably forefather of the concept of mixing martial arts – Bruce Lee. He stated that "power isn't generated by your contractile muscles but from the impetus and speed of your arm or foot" [1]. and linked this to successful combat, saying that "All the strength or power you have developed… is wasted if you are slow and can't make contact. Power and speed go hand in hand. A fighter needs both to be successful." [1]. He then linked this to reaction time stating, "a good fighter should beat his opponent to the punch with lightning fast hands or out kick him with his quick lead foot… He must deliver proper kicks and punches instinctively, so his mind is free for strategy." [1]. Barnes (2005) has stated that,

Speed is a key attribute for success in competition or self defense. Reaction speed is often the sole difference between winning and losing a physical confrontation. Regardless of your fighting style or method – you cannot apply it unless you can react quickly and respond accurately [2].

These same concepts of power, speed and reaction time appear again when Lee described "a perfect attack is the blending of strategy, speed, timing, deception and keen judgement." [1]. That is, the process of seeing an opening or opportunity, the time it takes to recognize the opening and select an appropriate technique, and then to react and properly execute that technique. In Lee's The Tao of Jute Kune Do (1975), some of the "qualities" of a martial artist are listed and include: power, vision awareness, speed and timing; among other traits. Power in this context is exerting strength quickly, explosive force or the product of force and speed. Visual awareness incorporates perceptual speed and reaction time. Speed can be differentiated into perceptual, mental and performance aspects. Timing refers to both reaction time; i.e. the time from a stimulus to the beginning of muscle movement and the movement time; i.e. the time from the beginning of muscle movement to the completion of contraction [3]. It should be mentioned that these qualities, identified by practitioners, can be scientifically investigated as experimental parameters.

Aspects of these concepts have been investigated scientifically through various indirect and direct means. Indirect methods include; accelerometers [4–8], dynamometers [9–12], electromyography [4,8,10–21], motion capture or high speed cameras [6,8,13,15,17,19,21–40], photocells or timers [32,41–43], simple reaction tests [14,16,44,45], photography/cinematography [4,46], and biomechanical/physiological measurements of force such as grip strength and vertical jump [47–52]. Direct methods include load cells that require contact [33,35,35,53–55], ground reaction force plates [7,21,26,32,33] and instrument/sensor equipped bags, dummies, or targets [5–8,43,46,56–59]. It should be noted that these target sensors are essentially types of load cells, strain gauges or accelerometers.

In summary, the above studies provide partial perspectives on martial arts techniques due to some limitations that exist in various research approaches. These limitations, and studies in which they can be found, include: kinematic or kinetic investigations not being full body or utilizing singular/limited cameras [8,13,17,19,23,24,31,32,34], absence of three dimensional motion analysis [4–7,16,22,41–43,46,56–59], using only three dimensional motion analysis [27–29,37–40], using lab based forces and controlled movements (dynamometers and load cells) [(9–12,20], utilizing collision mechanics [22], unrealistic targets (load cells or force plates) or no contact [(4,17–19,22, 31–36,46,53–55], non holistic view of the movement providing only one aspect or limb [8], non striking martial arts such as judo or tai chi [15,21,26,30], limited subject numbers [21,22,27,38,40], lab based reaction times [14,16,44,45] and indirect physiological tests [47–52].

Due to the limitations of previous works, the need for real/quasi real life applications and measurement of motor skills similar to reality as desired by practitioners and athletes; there is a need for new methods of quantifying martial arts striking power and reaction time. We propose to introduce such a method. The quantification was based on the strike timing, EMG measurement, 3D kinematic characteristics of the punching bag and striking limbs analyzed with self-developed programs. Reaction time was investigated by synchronizing the motion capture system with electromyography and a self-developed optical signal system. This allows for the breakdown of total reaction time into central or neural reaction and peripheral or muscular reaction. Our goal is to supply real-time feedbacks, such as punching and kicking power as well as related reaction for coaches and athletes in a quasi-training environment. We hope that the introduced method in this paper will lay the foundation for explorations of martial arts from a perspective that is closer to reality.

Material and Methods

Overview: Quasi-training environment set-up for real-time feedback

When an athlete is training for any sport, a coach tries to create a training environment that will mimic the real-life situations that an athlete might meet for that sport as closely as possible in order to prepare the athlete for the situations they will encounter in their sport. When testing sport specific techniques, it is also important that the environment closely resemble the real-life situations that the sport will encounter. The method used in this experiment was developed based on an environment

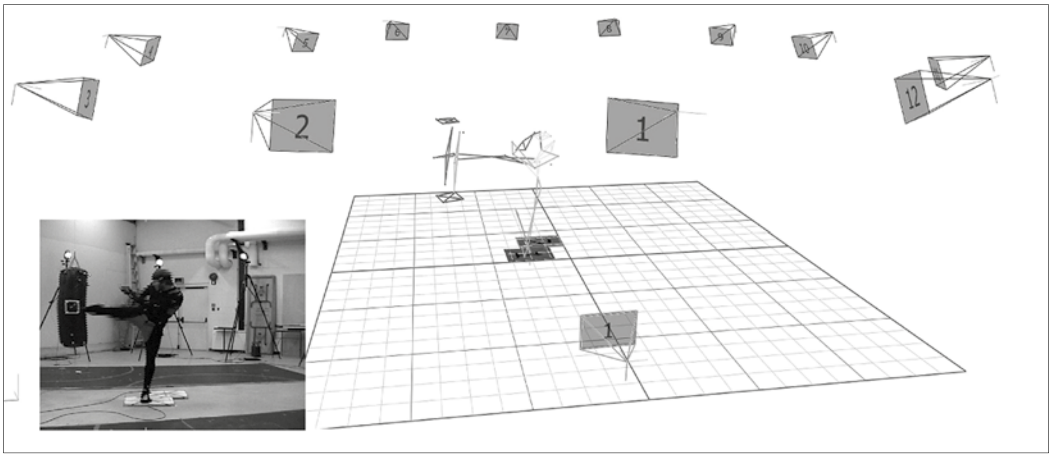

Figure 1. The set-up of synchronized 3D data collection.

that would closely represent a typical training environment for a martial artist in order to allow for more accurate, sport-specific feedback. The room was set up with a 3-D motion capture system, capturing the whole body movements of the subjects' every move. We also synchronized the EMG and a self-developed optical signal system with the 3D motion capture. The EMG data is used to determine the muscle response throughout the course of the movements. Our experimental set-up is designed so that it can provide real-time feedback for the athlete and for the coach, in order to maximize the training effects of each session.

3-D motion capture, biomechanical modeling and power determination

A twelve-camera VICON 3D motion capture system (Oxford Metrics Ltd., Oxford, England) was used to quantitatively determine the whole body kinematic characteristics during each movement. VICON software (Life Sciences Software Package, 2010) was configured to capture motion at a rate of 200 frames per second and reconstruct the captured movements in 3D computer space. Calibration residuals were determined in accordance with VICON's guidelines and yielded positional data accurate within 1 mm.

Two subjects were used in this study. Subject 1 was 26 years of age, 188.5 cm tall and weighed 96.1 kg. At the time of testing, he had 9 years of training with 4 years of professional fighting experience. Subject 2 was 25 years of age, 176.0 cm tall and weighed 75.6 kg. He had 3 years of training. Subject 2 also had years of athletic resistance training including Olympic/power lifting and was a strength and conditioning coach.

Each subject wore a stretchable, black garment with whole-body coverage. Affixed to the garment were 39 reflective markers, each with a diameter of 9 mm. The markers reflect infrared light to the cameras positioned around the subject (Figure 1). Four markers were placed on the head – one each on the left and right temples and two on the posterior portion of the parietal bone. Markers on the upper body were placed on the sternal notch, xiphoid process, C7, T10 and right back, the acromion processes, lateral epicondyles of the humerous, styloid processes of the ulna and radius, third metacarpophalangeal joint, as well as the upper and lower arm on both the right and left side. Markers on the lower body were also placed on both the right and left sides of the body in the following locations; the anterior superior iliac crest, posterior superior iliac crest, lateral condyle of the tibia, lateral malleolus of the fibula, calcaneal tuberosity and the head of hallucis, as well as on the upper and lower leg. The raw kinematic data was processed using a five-point smoothing filter (1-3-4-3-1 function). From these 39 markers, a full body biomechanical model with 15 segments (head & neck, upper trunk, lower trunk, two upper arms, two lower arms, two hands, two thighs, two shanks and two feet) was built, using methods previously described [60,61], to determine segmental angles, joint angles and their ranges of motion during a punch or kick.

In addition, a standard punching bag was outfitted with 15 markers; eight of which were located on the top and bottom of the bag to provide the framework for the bag, and another seven markers, three vertical left markers, three vertical right markers and one front marker whose height was equivalent with the highest markers on the sides. The eight markers that provided the frame of the bag were used specifically to take the measurements required to determine the punching and kicking power of the athlete. The seven side markers correspond to the targets of the most common strikes: left jab (left straight punch) and right straight punch to the head, hooks to the head and body as well as left and right kicks to the legs, body or head. They were used to test athletes' reaction by indicating to them the level of attack; high, middle or low through the optical signal system.

These target markers, combined with carefully placed striking markers on the middle knuckle of the glove and lower shin, allow for an investigation of accuracy. The shin marker was placed at the lower third of the shank and then adjusted based on the subjects' preferred contact area. The height of the bag was standardized by hanging the bag so that the middle or body targets were equal to the subject's lowest lateral rib, with the height of the force plates added. The high/head and low/leg targets are placed at 20% of body height away from midpoint marker, which is already located at the middle of the bag. The optical signal system consisting of three LED lights was initiated by a remote trigger controlled by the researcher. These lights were used to initiate the time of strike as well as to indicate to the subject the location of (or style of) strike. This data was integrated (synchronized) with the entire system. The lights were placed at the top of the bag at eye level without interfering with the targets. This allows for random selection of the strike within the chosen style and when combined with EMG and motion data allows for a thorough investigation of reaction time.

Kinematic data such as positional changes, velocities and accelerations, were calculated based on data collected from the 3D motion capture system. Power and force were also mathematically determined from the velocity and acceleration data obtained.

Using this experimental set-up we were able to determine the power in the kick or punch based on the movement of the punching bag in 3-D space. Using this information and treating the target object (punching bag) as a rigid body we were able to calculate the linear power and the angular power, and hence calculate the total power.

$$P_T = P_L + P_A \quad [1]$$

where P_T is the total power, P_L and P_A are the linear power and the angular power respectively.

Linear power quantification

In order to quantify linear power, we needed to first determine $\bar{v}$, the velocity of the centre of the bag and $\bar{F}$, the force applied to the bag.

From the 3-D motion capture system we were able to get information of the coordinate of each of the 8 corners of the punching bag. Since the punching bag is a cylindrical shape it is symmetric in both vertical and horizontal directions. Having a uniform density we were able to determine the centre of mass of the bag with coordinates x, y, and z, in their respective planes.

Using the coordinate data we were able to produce vectors representing the movement/position, velocity (first derivative of eq 2) and acceleration (second derivative) of the rigid body frame by frame. We then were able to perform basic physics calculations to calculate the linear force ($\bar{F}$) exerted on the bag (Newton's 2nd Law, eq 3). Using physics theory we were able to calculate the linear power of the action.

$$\begin{cases} v_1 = \dot{x} \\ v_2 = \dot{y} \\ v_3 = \dot{z} \end{cases} \quad [2]$$

Where $\bar{v}$ is the velocity vector of the centre of the punching bag, v_1, v_2 and v_3 are the velocities of the bag in the x, y and z-directions respectively, each determined by $\dot{x}$, $\dot{y}$ and $\dot{z}$, the first derivatives of the x, y and z-directions respectively.

$$\begin{cases} F_1 = m\dot{v}_1 \\ F_2 = m\dot{v}_2 \\ F_3 = m\dot{v}_3 \end{cases} \quad [3]$$

Where $\bar{F}$ is the force vector applied on the punching bag, m is the mass of the punching bag, and $\dot{v}_1$, $\dot{v}_2$ and $\dot{v}_3$ are the first derivatives of the velocities that were obtained previously, giving us the acceleration. Multiplying the mass of the bag, m with $\dot{v}_1$, $\dot{v}_2$ and $\dot{v}_3$ each individually gives us F_1, F_2 and F_3, the applied force in the x, y and z-directions respectively.

$$P_L = \vec{F} \cdot \vec{v} = F_1 v_1 + F_2 v_2 + F_3 v_3 \quad [4]$$

A program written in MATLAB was used to help us determine the linear power.

Angular power quantification

The determination of angular power needs the timely determination of the rotational characteristics of the bag during limb contact. Again, using the coordinate information obtained from the 3-D motion capture system, we were able to determine the positional vectors in each frame. Based on engineering physics [62], the rotational characteristics and angular power can be done using the Euler Angle System and angular dynamics.

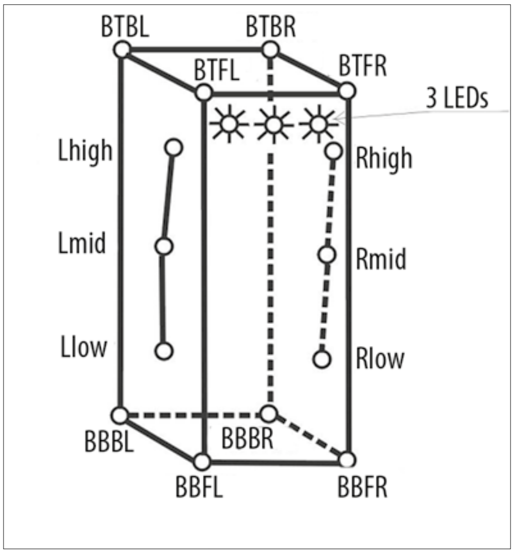

Figure 2A. Punching bag set-up. BTBL – bag top back left, BTFL – bag top front left, BTBR – bag top back right, BTFR – bag top front right, BBBL – bag bottom back left, BBFL – bag bottom front left, BBBR – bag bottom back right, and BBFR – bag bottom front right represent the markers on the eight corners of the bag. Markers were also placed on the sides to provide an aim for the subject Lhigh, Lmid, and Llow, Rhigh, Rmid and Rlow.

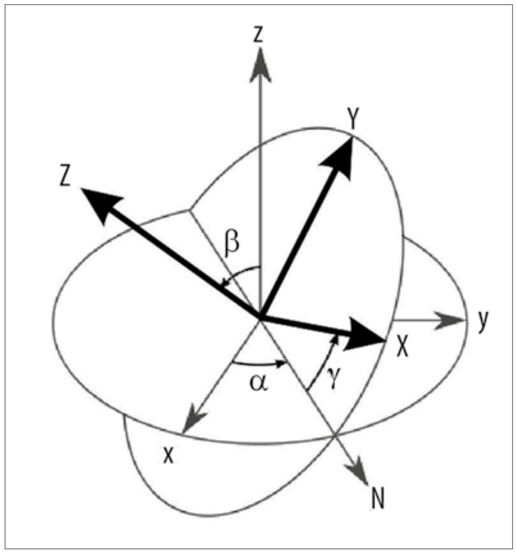

Figure 2B. Euler angle principles, used to represent the angular rotation of the punching bag. Lower case letters x, y and z represent the initial axis of an object, and capital letters *X*, *Y* and *Z* represent the axes after rotation. N represents a common line between the position before and after rotation (an intersection of the xy and the XY planes). The Euler angles α, β and γ represent the angle between the x-axis and N, the angle between the z-axis and the Z-axis and the angle between N and the X-axis respectively.

Euler angles (α, β, and γ) are used to represent any three consecutive rotations of a rigid body (Figure 2). Based on previous methods [63] we needed to calculate an angle between two vectors found in consecutive frames (timely change of a selected vector) in order to determine Euler angles. Such a vector in our method was chosen from the center of the bag to the bag top back right (BTBR). Again, using the coordinate information obtained from the 3D motion capture system, we were able to determine the positional vectors in each frame. These vector positions build a rotational matrix by Euler's theorem, which states that any 3D rotation can be represented by a rotation around a unit vector $\vec{n}=[n_1,n_2,n_3]^T$ The determination of $\vec{n}$ can be obtained using the dot product of the vector positions (the angle between vectors is expressed using θ, which were determined using 3D data from frame to frame). Once the $\vec{n}$ is determined, the rotation matrix (R) can be expressed as follows:

$$R = I\cos\theta + (1-\cos\theta)\begin{bmatrix} n_1^2 & n_1n_2 & n_1n_3 \\ n_2n_1 & n_2^2 & n_2n_3 \\ n_3n_1 & n_3n_2 & n_3^2 \end{bmatrix} + \sin\theta\begin{bmatrix} 0 & -n_3 & n_2 \\ n_3 & 0 & -n_1 \\ -n_2 & n_1 & 0 \end{bmatrix} \quad [5]$$

where I is identity matrix, i.e. $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

On the other hand, when the rotation matrix R is expressed using Euler Angle (α, β, γ), it has the following form:

$$R = \begin{bmatrix} \cos\beta\cos\gamma & -\cos\beta\sin\gamma & \sin\beta \\ \sin\alpha\sin\beta\cos\gamma & -\sin\alpha\sin\beta\sin\gamma+\cos\alpha\cos\gamma & -\sin\alpha\cos\beta \\ -\cos\alpha\sin\beta\cos\gamma+\sin\alpha\sin\gamma & \cos\alpha\sin\beta\sin\gamma+\sin\alpha\cos\gamma & \cos\alpha\cos\gamma \end{bmatrix} \quad (6)$$

From Eqn 5 and Eqn 6, we can determine α, β and γ. After Euler angles were obtained, the angular velocity of the bag in 3D space could be calculated based on Eqn 7 [62].

$$\begin{cases} \omega_1 = \dot{\alpha}\sin\beta\sin\gamma + \dot{\beta}\cos\gamma \\ \omega_2 = \dot{\alpha}\sin\beta\cos\gamma - \dot{\beta}\sin\gamma \\ \omega_3 = \dot{\alpha}\cos\beta + \dot{\gamma} \end{cases} \quad [7]$$

Where w_1 represents the angular velocity in the x-axis, obtained by taking the first derivative of the related Euler angles. Similarly, w_2 and w_3 represent the angular velocity in the y-axis and z-axis respectively.

In order to calculate the angular power, we needed to determine the moment of inertia of the bag. Treating the punching bag as a rigid body with a cylindrical shape we are able to obtain its moment of inertia.

$$\begin{cases} I_1 = I_2 = \frac{1}{12}m(3r^2 + h^2) \\ I_3 = \frac{1}{2}mr^2 \end{cases} \quad [8]$$

Where m is the mass of the punching bag, r is radium of the bag, h is the height of the bag, I_1, I_2 and I_3 are the moment of inertia in the medial-lateral, anterior-posterior and vertical directions respectively. Because the punching bag is symmetric they are equal to each other. After the determinations of angular velocities (Eqn7) and the moments of inertia (Eqn8), we could calculate the moment $\vec{M}$ (torque) applied to the bag using Euler equations (Eqn 9):

$$\begin{cases} M_1 = I_1\dot{\omega}_1 + (I_3 - I_2)\omega_2\omega_3 \\ M_2 = I_2\dot{\omega}_2 + (I_1 - I_3)\omega_3\omega_1 \\ M_3 = I_3\dot{\omega}_3 + (I_2 - I_1)\omega_1\omega_2 \end{cases} \quad [9]$$

Where, M_1, M_2 and M_3 represent the components of moment (or torque) in the x, y and z-axis respectively. I_1, I_2 and I_3 are the moments of inertia, w_1, w_2 and w_3 represent the angular velocities as previously calculated and $\dot{w}_1$, $\dot{w}_2$ and $\dot{w}_3$ represent the angular accelerations in the x, y and z-axis, obtained by taking the first derivative of w_1, w_2 and w_3.

Finally, we were able to calculate our angular power (P_A) by multiplying these three torques (M_1, M_2, M_3) by the corresponding angular acceleration values (w_1, w_2, w_2) and finding the magnitude of those vectors.

$$P_A = \vec{M} \cdot \vec{\omega} = M_1\omega_1 + M_2\omega_2 + M_3\omega_3 \quad [10]$$

A sample of power determination (both linear and angular power) using our method is shown in Figure 3. The figure contrasts the differences between a straight and a hook. As expected, a hook technique generated higher maximal power than a punch one, while a punch technique had longer bag contact time than a hook one.

EMG measurement and reaction time quantification

One of the synchronized devices in the unit was a surface electromyography (EMG) system. The EMG records electrical activity associated with neural firings in musculature. A neural pulse train is transmitted by the muscle fibers associated with a desired movement. Each neuron innervates several muscle fibers. The resulting raw EMG signal detected by surface electrodes, placed approximately over the belly of the muscle, is a summation over the ensemble of pulse trains associated with the muscle. The signal spectrum ranges from 0 to approximately 500 Hz. In the current method, an eight-channel, wireless NORAXON (NORAXON U.S.A., Inc., Arizona, U.S.A.) EMG with a gain of 1000 times was used to determine selected muscle activity. NORAXON's hardware specifications provided raw signal recordings at a rate of 1000 Hz with a band pass filter of 16–500 Hz. This allowed an investigation of muscular recruitment, activation and onset differences. The use of a wireless EMG system minimizes the constraints that normally occur with the use of wired electrodes, where subjects' dynamic movements and motor control patterns may be inadvertently altered due to the presence of wires connecting the subject to the measuring system.

The design of this set-up allowed us to investigate reaction time of the athlete; one aspect of the fight that gives the competitor the advantage. Reaction time can be defined as the amount of time that has elapsed between the stimulation of an event, and the response to that stimulation. In this experiment, a LED optical signal system was used to indicate to the subject the start of the trial. When the subject saw the light, he/she were to start their punch or kick. The system gave the following signals for punch or kick: straight, left and right, as well as low, middle and high. Using the synchronized measurement of EMG, optical system and 3D motion capture, we were able to break down the measured reaction time into two segments; central nervous system (CNS) response time and peripheral nervous system (PNS) response time (Figure 4).

We found the CNS response time by measuring the time elapsed from the start of the stimulus (optical signal) until the beginning of the PNS response, which was measured using the EMG system to indicate the time where the initial muscle response occurred. We calculated this initiation of the muscle using the EMG envelope, finding the point where the reaction of the muscle was 20% of the peak contraction.

The determination of the initial muscle activation was obtained using the following established steps in the literature: 1) obtain EMG envelop using the Butterworth filter; 2) find the maximum EMG value from the EMG envelop; 3) calculate the mean and standard deviation value between the initial onset of the light signal and maximum value; 4) search the EMG from the point that the stimulus was initiated, until the maximum value discovered looking for any peak that had an EMG value of over $\mu + 1.3\sigma$ of the value of the max. [64] When the

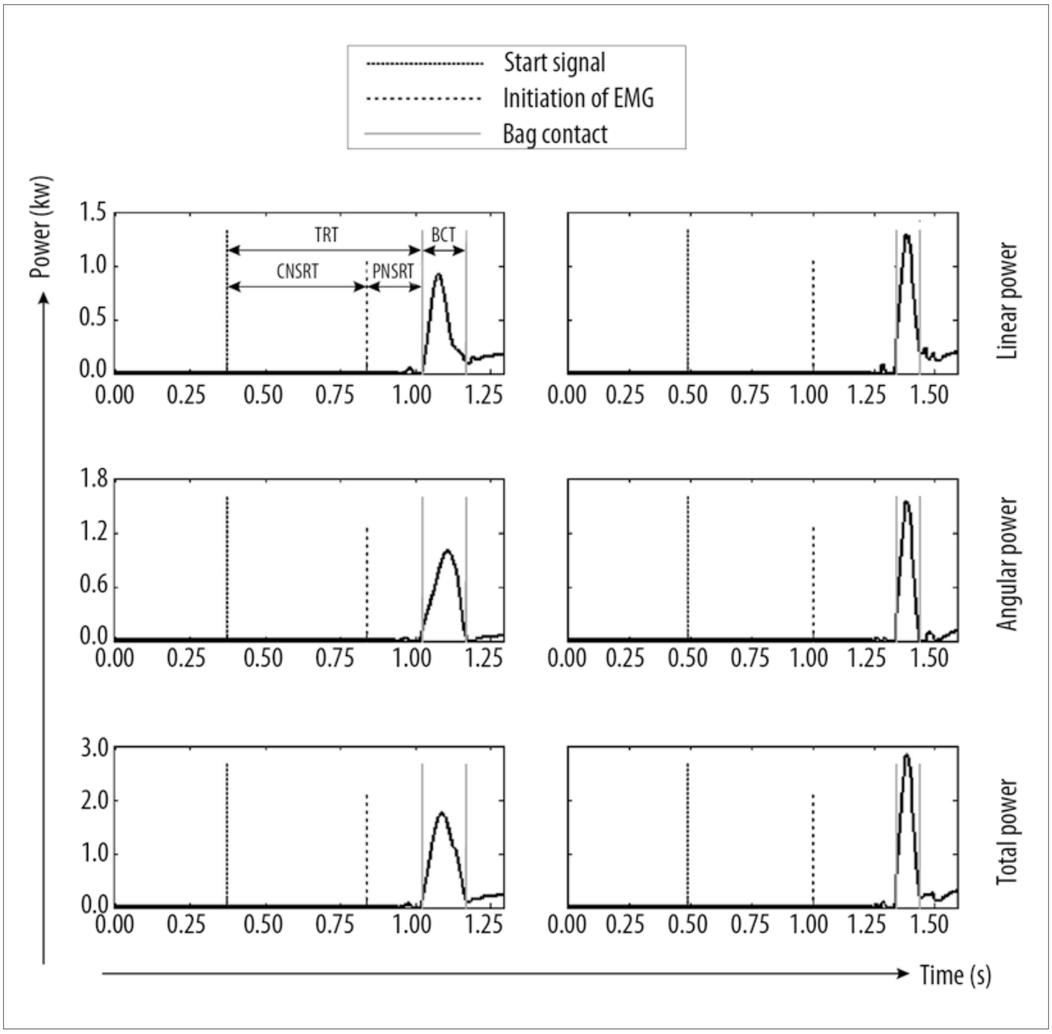

Figure 3. Typical power generation of a 185 lb athlete during a punch (right column) and a hook (left column).

first point satisfying this stipulation was found, we set that point as the start of the peripheral nervous system response time (Figure 4).

The PNS response time was measured from the initiation of the muscle response until the point of initial contact of the distal end of a limb with the punching bag, which was captured using the 3-D motion capture system.

The sum of these two aspects of the response gives the overall reaction time to a given stimulus. As discussed previously, two factors that give a fighter the advantage in a fight are power and fast hands, or in other words, a quick reaction time. If a fighter can train to reduce his reaction time he will have an advantage in a fight. By separating this reaction time into two components; CNS reaction and PNS reaction, a fighter is able to concentrate his training to improve the component of his reaction time that needs the most work. A coach can be provided with real-time feedback on the fighter's strengths and weaknesses and can be able to set up a training program that would help the fighter to minimize his reaction time, but it would also allow the coach to set up a fighting strategy that would maximize the strengths of the fighter.

Results

To validate the method, two subjects were used.

Two common techniques – the Right Roundhouse Kick and the Left Straight Punch – were selected and tested for both athletes. The results are shown in Figure 5. In terms of the kick power, the results demonstrated the following characteristics of the two individuals: Subject 1 attained a maximum linear power of 1771.7 watts with an average of 1063.0 watts, and a maximum angular power of 1215.7 watts with an average of 832.1 watts. These resulted in a maximum total power of 2987.4 watts with an average of 1895.1 watts. For Subject 2, the values of linear and angular power were 1707.5 watts, 1280.7 watts, 131.9 watts, and 90.2 watts respectively. These

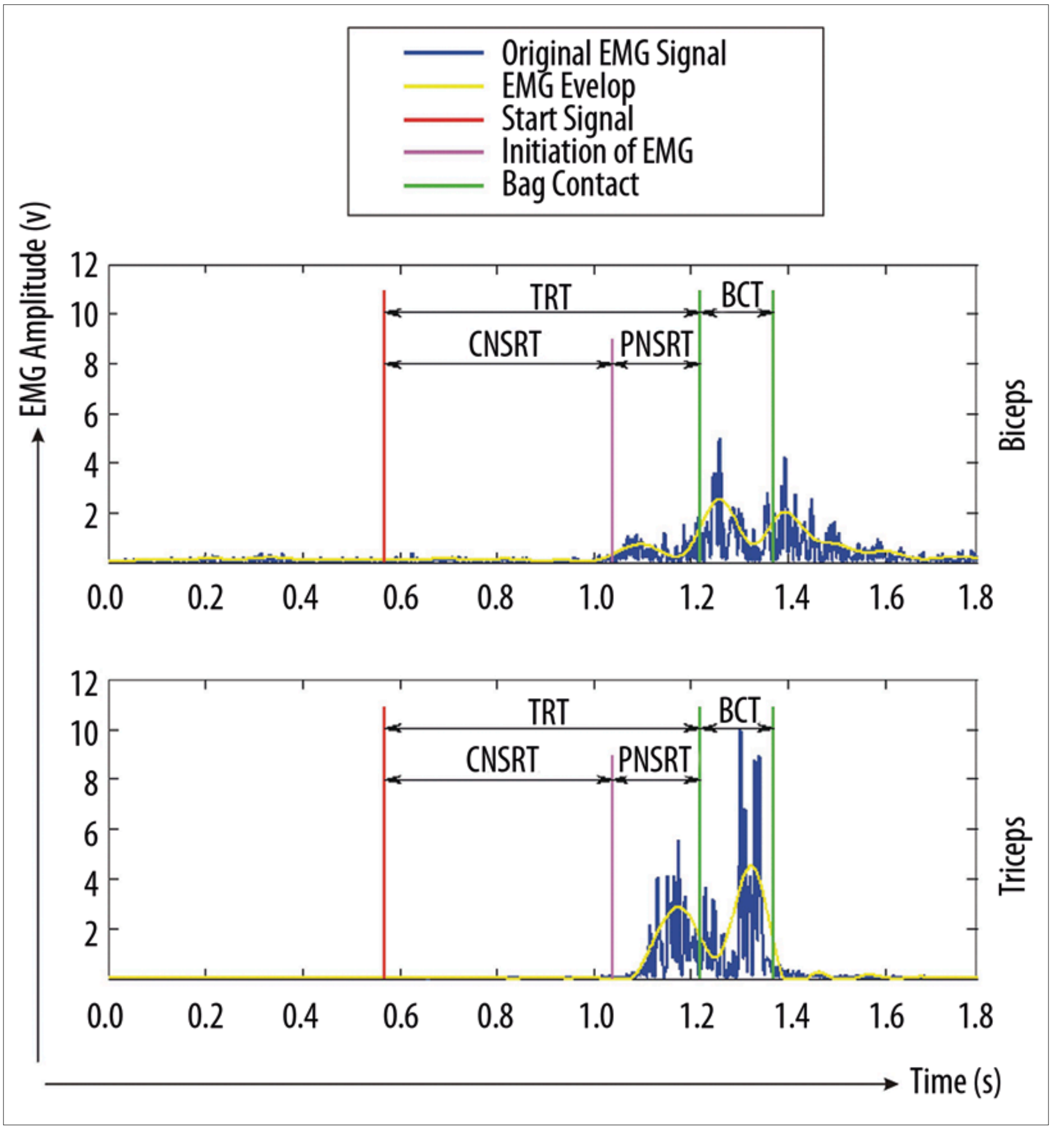

Figure 4. Quantification of reaction time using our synchronized device and EMG enveloping method.

values gave Subject 2 a maximum total power of 1778.6 watts with an average of 1370.9 watts.

In terms of neural response characteristics of the skill: Subject 1 had a total reaction time of 1.025 seconds; with neural reaction (CNS) taking 0.795 seconds and peripheral or muscular reaction accounting for 0.230 seconds. The value for Subject 2 was 0.675 seconds; with neural reaction (CNS) taking 0.190 seconds and peripheral or muscular reaction accounting for 0.485 seconds.

Whereas Figure 5 provides uniqueness of the two athletes on the Roundhouse kick, Figure 6 showed their individuality of the left straight punch. Subject 1 achieved a maximum linear power of 923.1 watts with an average of 468.4 watts, and a maximum angular power of 997.4 watts with an average of 618.8 watts. As such, Subject 1 generated a maximum total power of 1748.8 watts with an average total of 1087.2 watts. Subject 2 accomplished a maximum linear power of 707.9 watts with an average of 365.8 watts, and a maximum angular power of 1119.0 watts with an average of 685.9 watts. Consequently, Subject 2 achieved a maximum total power of 1596.0 watts with an average total of 1051.7 watts.

Further, Figure 6 showed the following reaction characteristics of the tested subjects. For Subject 1, the total reaction time was 0.65 seconds; with a neural reaction of 0.47 seconds and peripheral reaction of 0.18 seconds. Compared to Subject 1, Subject 2 had a faster reaction. His total reaction time was 0.43 seconds; with a neural reaction of 0.25 seconds and a peripheral reaction of 0.18 seconds..

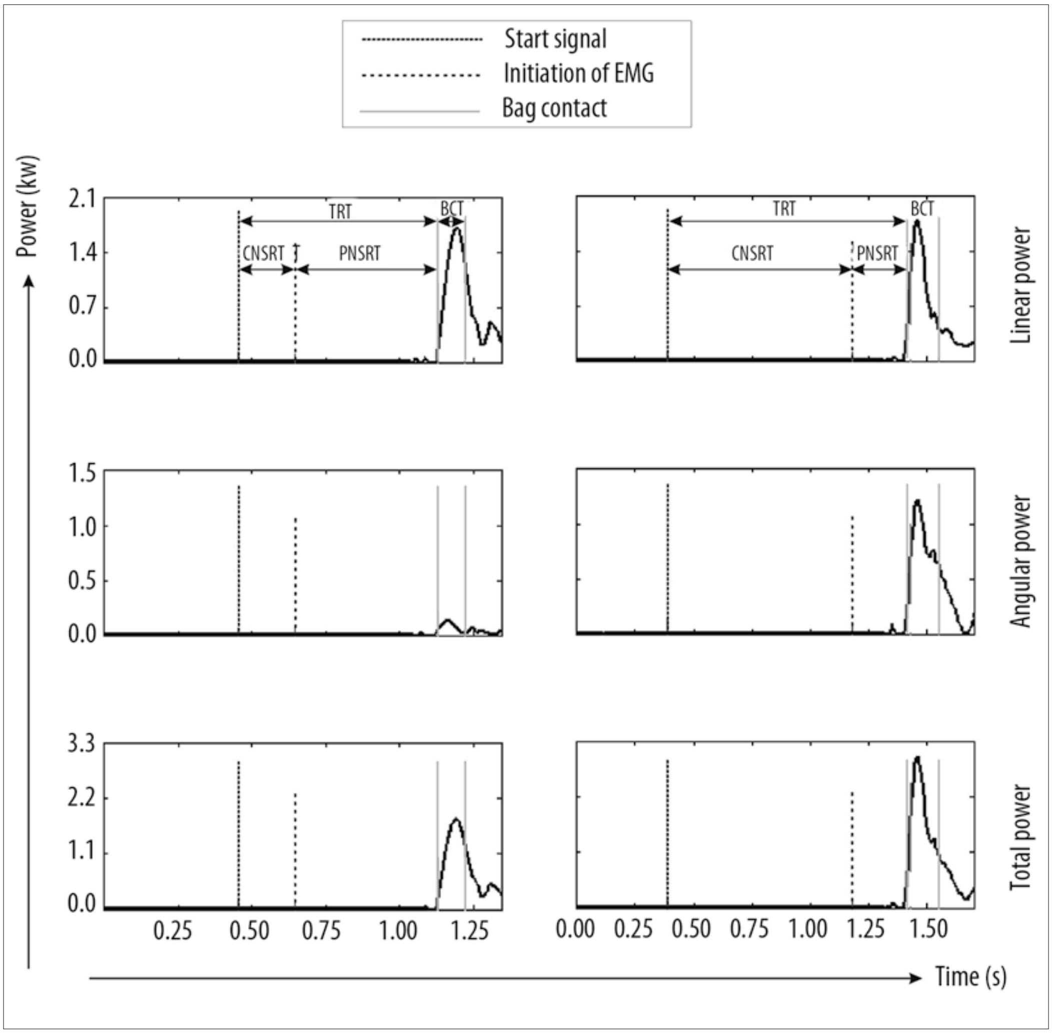

Figure 5. Comparison of the Right Roundhouse Kick of two martial arts athletes: right column – Subject 1; left column – Subject 2.

Discussion

One aim of this study was to quantitatively determine and describe the power outputs of various martial arts offense techniques. Results reveal that the quantifications of both total power and power components (i.e. linear and angular) supply insights for characterizing individuals and/or techniques. It is known that the total power depends mainly on the physical condition of an athlete, while the components/power distributions (linear/total and angular/total) are influenced by a technique applied, the attacking location and the posture at the impact/contact with the bag.

In a right roundhouse kick analysis, Subject 1 generated in average 53.1% more total power than Subject 2. Further, the results of components showed the difference between both subjects in detail: the power distribution was approximately equal for Subject 1 (56.1% linear and 43.9% angular, Figure 5), while the distribution was a disparity for Subject 2 (93.4% linear and 6.6% angular, Figure 5). By comparing the components of the two athletes, one could find that the linear power difference between the subjects could be neglected, while there were vast differences in angular power (maximum: 821.9% and average: 822.3%). As such, the difference in total power generation between the two subjects is mainly caused by the angular component. It is speculated that the distance between a target and an athlete is the key contributor. Distance is influenced by location of target contact (accuracy), leg length, location of contact on leg (foot contact compared to shin), foot position, angle of the supporting leg, joint positions and coordination (influence of ankle, hip, and knee angles as well as ankle/foot angle during contact). To resolve the questions of multiple factors, synchronized multidimensional 3D analysis should be applied.

For the left straight punch, the following characteristics of the two subjects were revealed; the total punch power

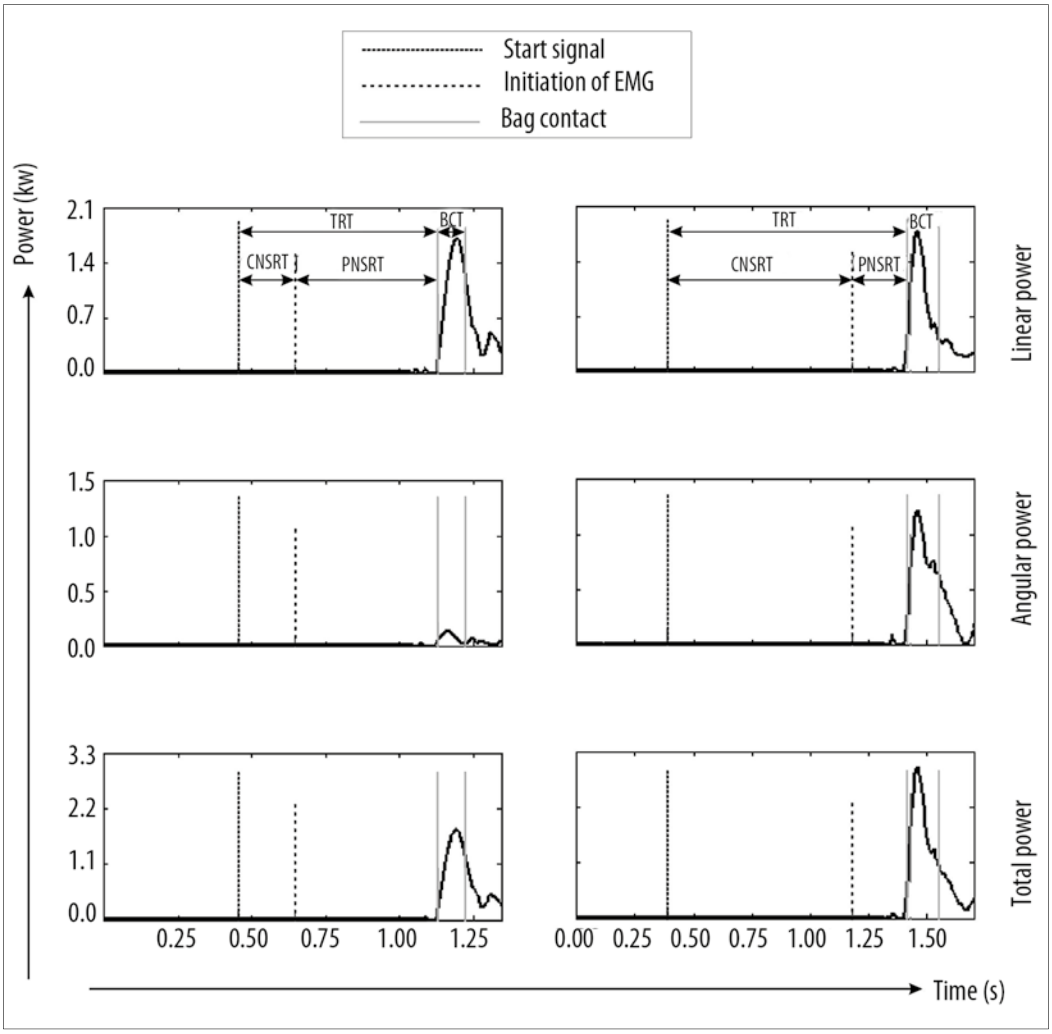

Figure 6. Comparison of the Left Straight Punch of two martial arts athletes: right column – Subject 1; left column – Subject 2.

outputs were similar (the difference <10%, Figure 6), although a significant difference existed in kick power between the two athletes. Second, Subject 1 punched more precisely than Subject 2. As known from Physics, the power distribution could be used to determine the accuracy of a punch: the higher percentage of the linear component, the closer the punch is to the bag center, therefore, the more accurate the punch is. Our results showed that the distribution of punching power of the left lead straight (or jab) were linear 43.1%, angular 56.9% and linear 34.8%, angular 65.2% for Subject 1 and 2 respectively. Therefore, Subject 1's punch was closer to the center/target than Subject 2's. One possible technique reason for losing or altering the straight attack angle and decreasing accuracy would be flaring the elbows away from the body instead of keeping them tight, e.g. possibly twisting the hand to horizontal as opposed to a straight vertical fist; also aiming straight on with the 1st and 2nd knuckles lining to the shoulder as opposed to angled punches. For revealing the myths of the issue, 3D motion analysis may be an efficient tool for further studies.

In practice, it is also desirable to compare different techniques for knowing the characteristics of various techniques in order to choose sparring strategies. Figure 4 shows a comparison between a Left Straight Punch and a Lead Left Hook of Subject 1. Contrary to an unequal distribution in the punch, the power distribution of the hook was approximately equal (linear 47.1% and angular 52.9%). Further, the hook was considerably more powerful in every aspect than the straight (maximum linear +40.2%, average linear +93.6%, maximum angular +55.4%, average angular +64.5%, maximum total +62.7%, average total +77%). Some possible reasons include: the punch was with the lead left hand, not the stronger right hand, the hook is trained to be powerful with knockout power and speed. Also, there is an exaggerated hip/trunk rotation in the hook to maximize energy or force transfer and drive those forces from the ground through the body.

Collectively, these findings suggest that the quantification of power and its distribution provides a more effective means to examine individual techniques in martial arts. In combination with 3D motion analysis, the method would supply valuable insight and information for athletes and/or coaches to analyze individuals for optimization and/or effectiveness of offensive techniques.

Another main aim of the study was to quantify the neural response/reaction time during the performing of various techniques. As mentioned in the introduction, reaction is one of the fundamentals in many martial arts. The results showed that Subject 1 was slower in almost all aspects of kicking and punching responses except for PNS – left arm movement (kick: CNS +318.4%, PNS +110.9%, Total +51.9%, punch: CNS +88%, PNS 0%, Total +51.2%). The results showed that the biggest difference between the two subjects was the central nervous system (CNS) response.

The peripheral nervous system (PNS) response could be influenced by multiple factors, including distance to the target, body dimension and techniques applied. All the influence factors could be linked to a key parameter – distance covered by a limb movement. This speculation was confirmed by the comparison between a punch and a hook of Subject 1 (Figure 4). While the difference of CNS was around 10%, the PNS response of the hook was 86.1% more than that of the straight punch. This suggested that a hook needs the distance closed for an effective strike, i.e. the need to "set up" the hook with other strikes or combinations for effective use. This might indicate, a taller athlete needing more PNS response time to move his or her limb to reach a target than a shorter one. In combination with power analysis, the above results portrayed two different athlete types in our subjects: taller-slower and shorter-faster. Further studies are needed to investigate these expectations.

In summary, the method introduced in this study provides a quantitative way to analyze individual power generation and its related response process/time using various offensive techniques in martial arts. Such quantitative information would add complementary insights to motion analysis, allowing a more holistic assessment of athletes' technical ability, which, in turn provides foundational information for decision making regarding sparring strategies, biofeedback training and development of new training methods.

One potential application of the new method is to use it in a real-time biofeedback environment. During such training, quick feedback of power generation, attack accuracy, central and peripheral reaction time on various offensive techniques could: 1) motivate athletes as their perspective of punching power and reaction time is simultaneously supplied, 2) improve athletes' perception system in order to develop competition strategies (e.g. avoid slower techniques if opponent has fast reactions), and 3) evaluate effect of various training methods or technique variances for training or skill optimization.

Conclusions

This study introduced an innovative method for quantifying power and neural response of martial arts striking in order to develop a real-time biofeedback training approach similar to realistic training environment. As such, this approach is especially useful for practitioners such as coaches and athletes. The quantification was based on a self-developed optical signal system, EMG measurement, 3D kinematic characteristics of the punching bag and striking limbs analyzed with self-developed programs. This approach provides quantifications of both total power and power components (i.e. linear & angular) of striking and the related response processes/time. The results of this study showed that the method offers feedback of power intensity, attack accuracy, central and peripheral reaction time, demonstrating its great potential to become a biofeedback tool in practice. Such detailed information can help coaches and athletes identify weaknesses of approach and/or technique, which can lead to modification of individual training programs in order to increase training efficiency and effectiveness.

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