Evidence of a Double Peak in Muscle Activation to Enhance Strike Speed and Force: An Example With Elite Mixed Martial Arts Fighters

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ABSTRACT

McGill, SM, Chaimberg, JD, Frost, DM, and Fenwick, CMJ. Evidence of a double peak in muscle activation to enhance speed and force: an example with elite mixed martial arts fighters. *J Strength Cond Res* 24(2): 348–357, 2010—The main issue addressed here is the paradox of muscle contraction to optimize speed and strike force. When muscle contracts, it increases in both force and stiffness. Force creates faster movement, but the corresponding stiffness slows the change of muscle shape and joint velocity. The purpose of this study was to investigate how this speed strength is accomplished. Five elite mixed martial arts athletes were recruited given that they must create high strike force very quickly. Muscle activation using electromyography and 3-dimensional spine motion was measured. A variety of strikes were performed. Many of the strikes intend to create fast motion and finish with a very large striking force, demonstrating a "double peak" of muscle activity. An initial peak was timed with the initiation of motion presumably to enhance stiffness and stability through the body before motion. This appeared to create an inertial mass in the large "core" for limb muscles to "pry" against to initiate limb motion. Then, some muscles underwent a relaxation phase as speed of limb motion increased. A second peak was observed upon contact with the opponent (heavy bag). It was postulated that this would increase stiffness through the body linkage, resulting in a higher effective mass behind the strike and likely a higher strike force. Observation of the contract-relax-contract pulsing cycle during forceful and quick strikes suggests that it may be fruitful to consider pulse training that involves not only the rate of muscle contraction but also the rate of muscle relaxation.

Key Words striking, electromyography, muscle stiffness, muscle relaxation

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24(2)/348–357

Journal of Strength and Conditioning Research

Introduction

The muscle force-length relationship together with the muscle force-velocity relationship form a family of curves linked to activation level of the muscle (19). Thus, higher levels of neural stimulation to a muscle creates more force, stiffness, and viscosity, which translates to more resistance to length change and speed (3). This appears paradoxical for fast, forceful tasks because muscle force is needed to create limb speed yet the accompanying stiffness would slow the joint motion and reduce speed. We have measured the muscle activation patterns in a wide variety of speed/strength athletes and documented the "pulsing" of activation to optimize speed and strength. In this way, pulses of activation input strength to the linkage, whereas phases of relaxation allow speed to develop. We chose mixed martial arts (MMA) fighters as a study group to see whether they used a similar mechanism to achieve very rapid striking limb motion while creating a very high strike force. Thus, this descriptive study formed a test of "proof of principle" to help identify some basic variables that contribute to speed-strength performance together with providing some description of strike mechanics.

Several studies have documented features of various strikes consistent with different styles of martial arts. A few have contributed to the notion of speed and increased striking force. For example, Walker (17) conducted a theoretical analysis and noted that the "effective mass," that is, the mass in motion, added to the impact force. Although not directly stated, stiffening the body upon impact would add to the effective mass of the striking hand or foot. Blum (1) suggested that a "high mass" could be enhanced by stiffening the upper limb and torso upon impact. Smith and Hamill (16) tested gloves and noted that higher-skilled boxers imparted more momentum to a bag even though the hand was not travelling at a higher velocity. They suggested that the skilled boxers created a higher effective mass. Neto et al. (12) performed an elegant experiment in which kung fu practitioners struck a basketball using a palm strike technique. By controlling several variables, they concluded that effective mass was important in creating a high strike force and that it was dependant on variables other than body mass. They further concluded that the candidate mechanism was stiffening of the "appropriate muscles" just before impact. Pain and Challis (13) noted that muscular stiffening reduced the energy losses in the forearm together with arm positioning to enhance the effective mass during strikes. Given these thoughts, martial arts styles appear to differentiate the role of stiffening and effective mass enhancement from that of enhancing strike speed. This may be a result of speed being an important determinant of kinetic energy. For example, Wilk et al. (18) conducted a more in-depth analysis of karate strikes and the physics of breaking boards and concrete slabs and concluded that, theoretically, the speed of the striking hand or foot was important because of the velocity squared term in any calculation of kinetic energy upon impact. However, speed of impact to enhance the landing force is a separate issue from speed of the hand or foot travelling to the target. Obviously, higher speed to close the distance to an opponent would be better. Even so, Falco et al. (5) noted that body mass was a better determinant of impact force than distance in roundhouse kicks, although "effective mass" was not considered. The literature suggests that effective mass is important in enhancing the strike force and that a candidate mechanism is muscular stiffening. This background motivated the present study.

Given that effective mass has been suggested to be an important determinant of enhancing the strike force, and because speed is an objective measure, the purpose of this study was to document the type of muscle contraction profiles during strikes. Elite MMA athletes were recruited to provide insight into this question on the influence of the type of eventual strength training needed to enhance this type of speed/strength performance.

Methods

Experimental Approach to the Problem

Electromyography (EMG) and 3-dimensional spine motion were recorded as well as video of both the frontal and sagittal planes while fighters struck a heavy bag used for training. The bag had a "strike strip" that sent a signal upon impact to the collection system to synchronize the various signals.

Subjects

Five MMA fighters (all veterans of the Ultimate Fighting Championship [UFC] and 1 world champion) with an average age, height, and body mass of 29 ± 1.8 years, 1.81 ± 0.03 m, and 91.9 ± 15.4 kg, respectively, participated in this study. All subject recruitment and data collection procedures were performed in accordance with the University Office of Research and Ethics guidelines.

Procedures

Sixteen Ag-AgCl surface electrode pairs (size 3 cm, round shape) were placed bilaterally with an interelectrode distance of approximately 2.5 cm on the following muscles: right and left rectus abdominis (RRA and LRA) lateral to the navel, right and left external obliques (REO and LEO) approximately 3 cm lateral to the linea semi lunaris but at the same level as the RRA and LRA electrodes, right and left internal oblique (RIO and LIO) caudal to the REO and LEO electrodes and the anterior superior iliac spine and still cranial to the inguinal ligament, right and left latissimus dorsi (RLD and LLD) over the muscle belly when the arm was positioned in the shoulder mid-range, right and left upper (thoracic) erector spinae (RUES and LUES) approximately 5 cm lateral to the spinous process (actually longissimus thoracis and iliocostalis at T9), right and left lumbar erector spinae (RLES and LLES) approximately 3 cm lateral to the spinous process (actually longissimus and iliocostalis at L3), right gluteus medius (RGMED) on the muscle belly found by placing the thumb on the anterior superior iliac spine and reaching with the fingertips around to the gluteus medius, right gluteus maximus (RGMAX) in the middle of the muscle belly approximately 6 cm lateral to the gluteal fold, right rectus femoris (RRF) approximately 15 cm caudal to the inguinal ligament, and right biceps femoris (RBF) over the muscle belly midway between the knee and hip. Before adhering the electrodes, the skin over each muscle was shaved and cleansed with a 50/50 H_2O and ethanol solution. The EMG signals were amplified to produce maximum signals approaching plus/minus 10 volts and then A/D converted with a 12-bit, 16-channel A/D converter at 2,048 Hz.

Each subject was required to perform a maximal contraction of each measured muscle for normalization of each channel (after Kavcic et al., 2004) (7). For the abdominal muscles, each subject adopted a sit up position and was manually braced by a research assistant. They then produced a maximal isometric flexor moment followed sequentially by a right and left lateral bend moment and then a right and left twist moment. Little motion took place. For the spine extensors and gluteal muscles, a resisted maximum extension in the Biering Sorensen position was performed (11). A specific RGMED normalizing contraction was also attempted with resisted sidelying abduction (i.e., the clam). Participants lay on their left side with the hips and knees flexed. Keeping their feet together, they abducted their right thigh to parallel, and a research assistant restricted further movement. Normalizing contractions for RRF were attempted with isometric knee extension performed from a seated position with simultaneous hip flexion on the instrumented side. For RBF, participants lay prone and were instructed to flex the knee and extend the hip while the researcher manually resisted both movements. The maximal amplitude

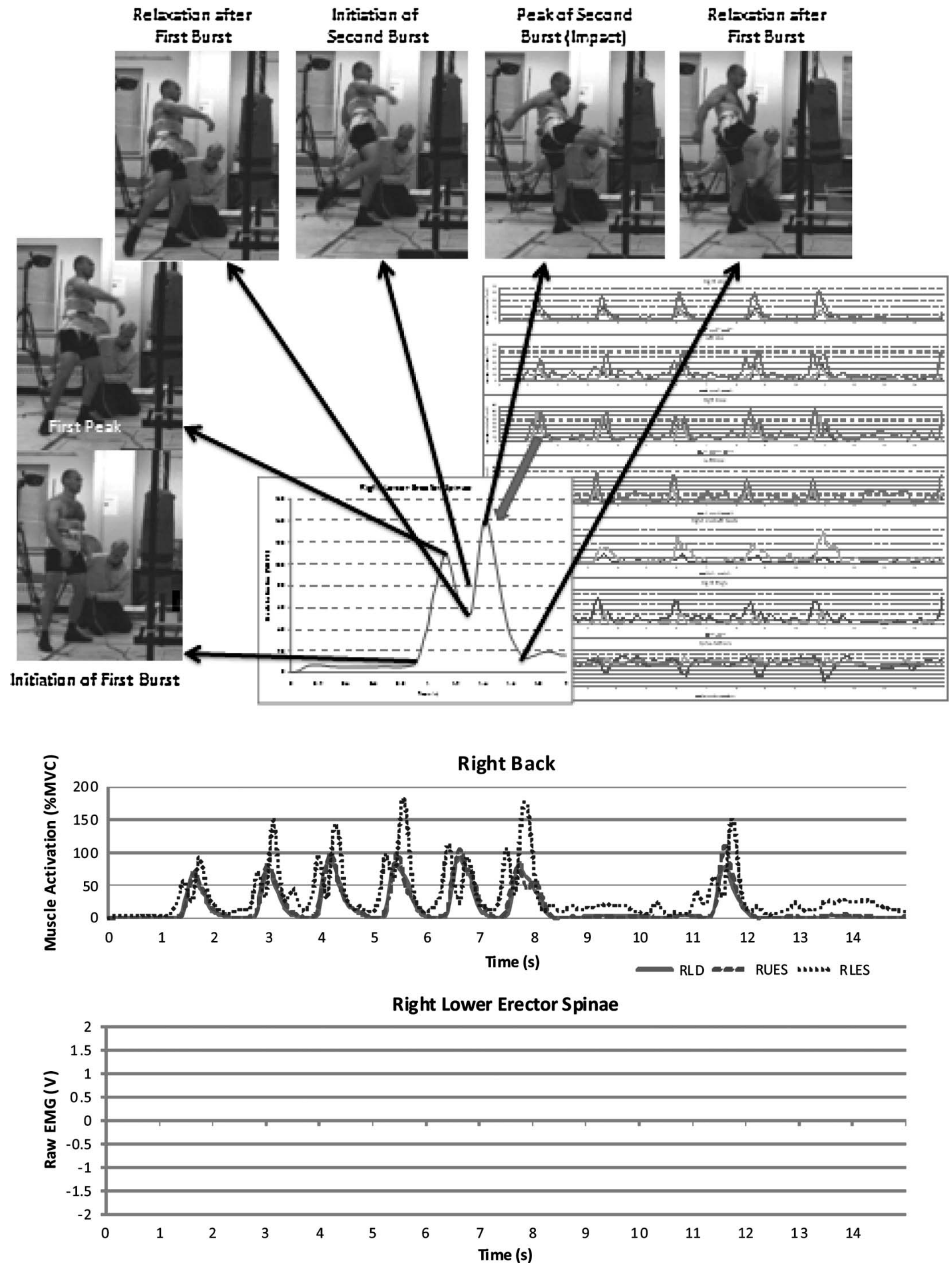

Figure 1. Electromyography from back muscles of highly trained athlete kicking a bag showing perfect ON/OFF pulses of erector spinae. First pulse is associated with stiffening of body to initiate leg motion, but foot is just in process of leaving ground. Then, as speed increases, muscles relax but undergo a second pulse to increase stiffness and effective mass as foot strikes bag.

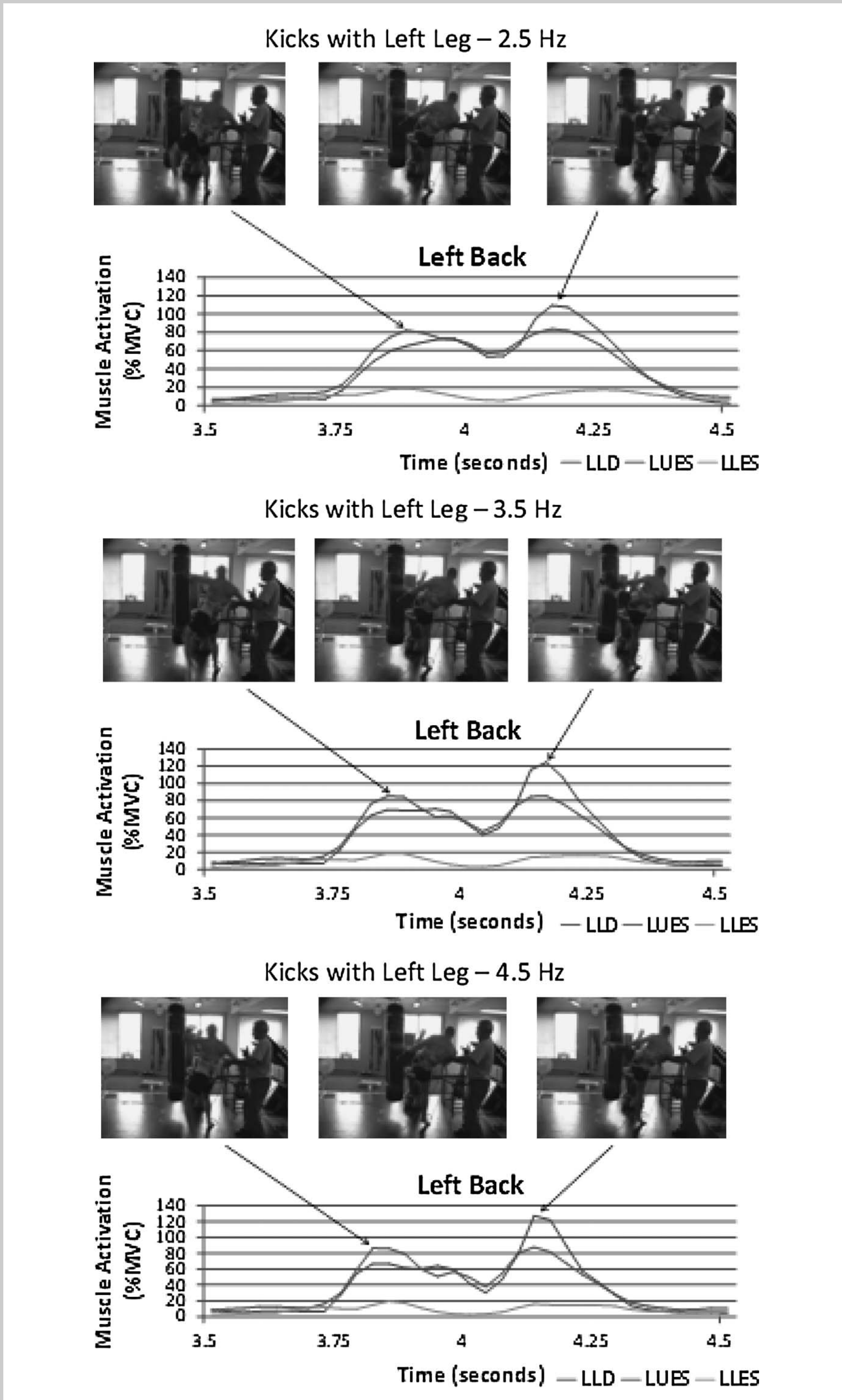

Figure 2. Choice of cut-off frequencies of low-pass filter to mimic frequency response of muscle did not have major influence on implications drawn from this data set. Contact of foot with bag was not substantially affected.

observed in any normalizing contraction for a specific muscle was taken as the maximum for that particular muscle.

The EMG signals were full wave rectified and low-pass filtered with a second order Butterworth filter. Initially, a cut-off frequency of 2.5 Hz was used to mimic the EMG to force frequency response of the torso muscles (2). Secondary sensitivity analyses were conducted using a cut-off frequency of 3.5 Hz and 4.5 Hz. The EMG signals were normalized to the maximal voluntary contractions to enable physiologic interpretation.

Lumbar spine position was measured about the 3 orthopaedic axes (flexion/extension, lateral bend, axial twist) using a 3 Space IsoTRAK electromagnetic tracking instrument (Polhemus, Inc., Colchester, VT, USA). This instrument uses a single transmitter that was strapped to the pelvis over the sacrum and a receiver strapped across the ribcage over the T12 spinous process. In this way, the position of the ribcage relative to the pelvis was measured (lumbar motion). Spine posture was normalized to that obtained during standing (thus corresponding to 0° of flexion-extension, lateral bend, and twist). For the purposes of describing deviations in spine posture in the Results section, absolute values of the lateral bend and twist angles are reported, and thus the reader will know when participants were more/less laterally bent/twisted during an event.

Video was collected at 30 Hz and digitized and interpolated or "up sampled" to 32 to synchronize with the 3 Space and the EMG data. Cameras were orientated to capture both a sagittal and a frontal plane view. The instant of impact on the bag was detected by a contact sensitive strip and recorded simultaneously with the EMG and spine motion data.

Description of MMA Strikes

Fighters were asked to hand strike and kick a heavy bag using different styles that they believed would result in both speed and a high contact force. Each fighter has their own arsenal of striking styles. Single hand strikes also included some combinations such as a jab/hook. Foot strikes included the roundhouse kick to the opponent's knee, hip, and head (simulated by appropriate strike zones on the bag) and also a side kick and a spinning back kick.

Data Analysis

With used of the recorded video, each trial (EMG, 3 Space, strike contact, and video) was sectioned from approximately 1 econd before the start of motion through to the completion of each striking task.

Testing Assumptions to Mimic Frequency Response of Muscle

Normalized EMG signals and lumbar spine position data were plotted and synchronized with specific events noted on the video images. The EMG data was compared with events of interest such as the instant that the foot left the ground during a kick or the instant of impact. Obviously, the choice of EMG low-pass filter cut-off frequency is tuned to mimic the frequency response of muscle and the transfer function between the electrical input (EMG) and the force output of the muscle. Past work determined the transfer function, including the electromechanical delay, of the erector spinae to include a low-pass filter cut-off frequency of approximately 2.5 Hz (2). Note that this assumption was later tested with sensitivity analysis.

Statistical Analyses

This study was not designed for statistical analysis because each fighter performed striking tasks in a different manner. The purpose here was to simply obtain data documenting motor patterns of the various strikes and not to determine differences between them. Thus, this was a basic science investigation to describe and characterize a movement task that has a simple purpose but may be accomplished differently by different individuals.

Results

Note that 100% maximum voluntary contraction (MVC) was obtained during isometric maximal efforts. Greater than 100% of this MVC is often seen when dynamic motion occurs. Because we were testing extremely fast strength efforts, we performed sensitivity testing of the EMG processing to ensure its validity and suitability. This is followed by the task results.

An Intriguing First Observation

During a test session before recruiting the MMA fighters, we tested a very highly trained coach (age 42 yr, height 1.76 m, weight 81 kg) who is extremely strong, quick, and proficient in kicking. His data showed exemplary pulses during kicks (Figure 1), which generated the hypothesis tested here. Filtered EMG linked to the phases of kicking are shown. Note the silence between the pulses on the raw EMG signal, illustrating the superb relaxation as the foot gained speed.

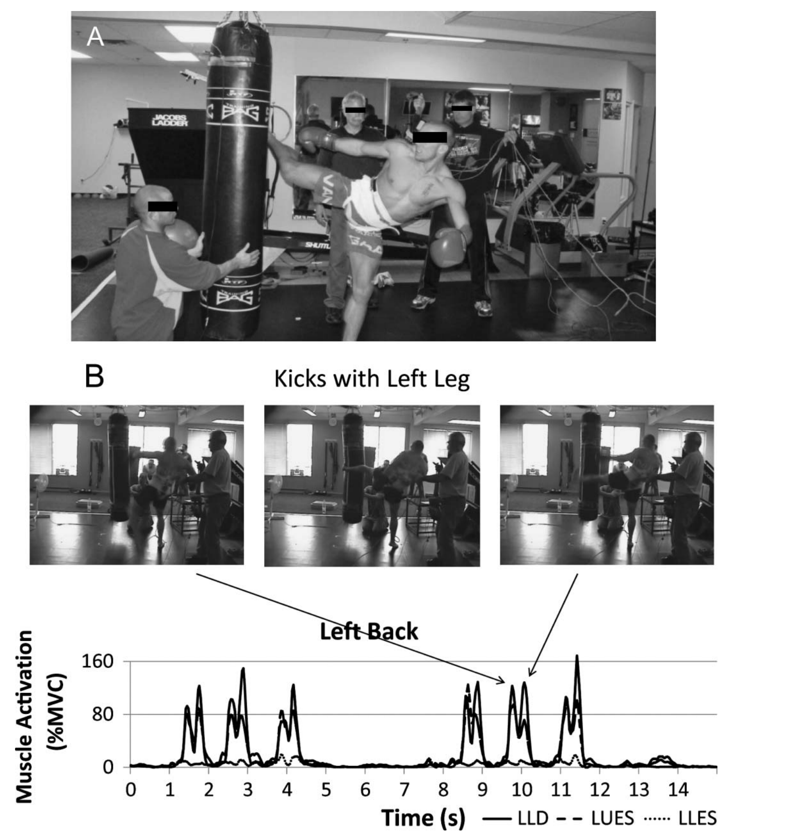

Figure 3. Leg kicks of elite fighters more typically produce double peaks. A) Stiffness enhances effective mass on contact to enhance strike. B) Multiple leg kicks (2 bursts of 3 kicks) shows double peak in muscle activity with each separate kick.

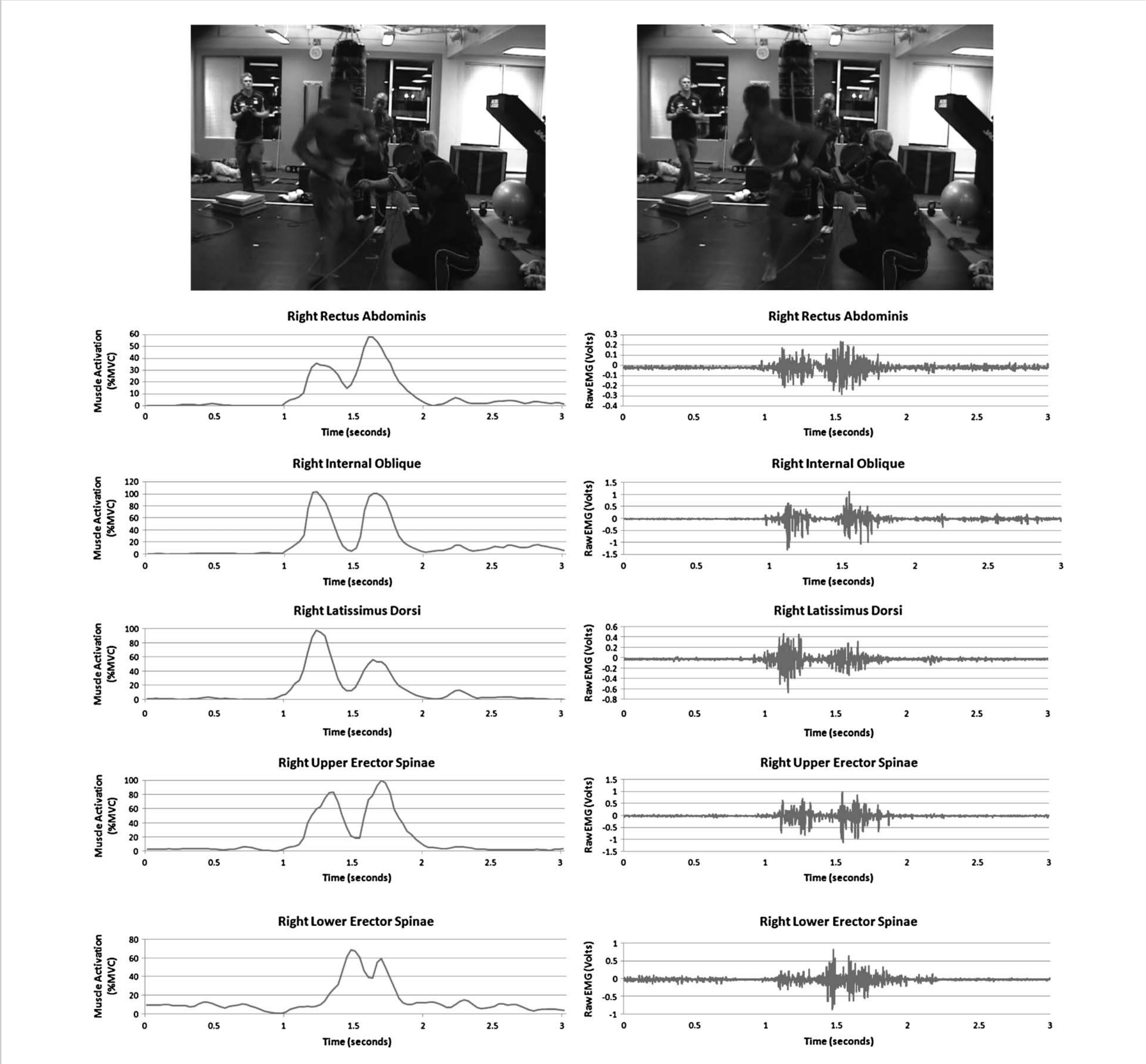

Figure 4. Raw electromyography (EMG) together with filtered EMG (mimicking force) shown during spinning back kick. Double peak is shown across muscles.

Sensitivity Testing

First, the EMG data was processed with a Butterworth low-pass filter with a cut-off frequency of 2.5 Hz to mimic the frequency response of torso muscle. This assumption was obtained from tests performed on a nonathletic population (2). However, elite athletes would be expected to have a shorter electromechanical delay mimicked by a higher low-pass filter cut-off frequency. We did not know whether these MMA athletes would have faster contraction/relaxation rates than nonelite athletes, so sensitivity testing was performed. Thus, 3 cut-off frequencies were tested (2.5, 3.5, 4.5 Hz) but had little effect on the interpretation of the timing data. For example, linking the EMG peaks during a left leg kick to events such as the foot leaving the ground (marked from the video records) or making contact with the bag was only shifted 1 frame (1/32 of s) over the cut-off frequencies of 2.5, 3.5, and 4.5 Hz (shown in Figure 2). Thus, cut-off frequency choice was not a sensitive variable, and it was assumed that the time course of the filtered EMG matched force production.

Examples of Strikes

Examples of different hand and foot strikes are shown together with some techniques known in MMA as "ground and pound." These are usually short strikes generated primarily with shoulder motion. The first peak of muscle

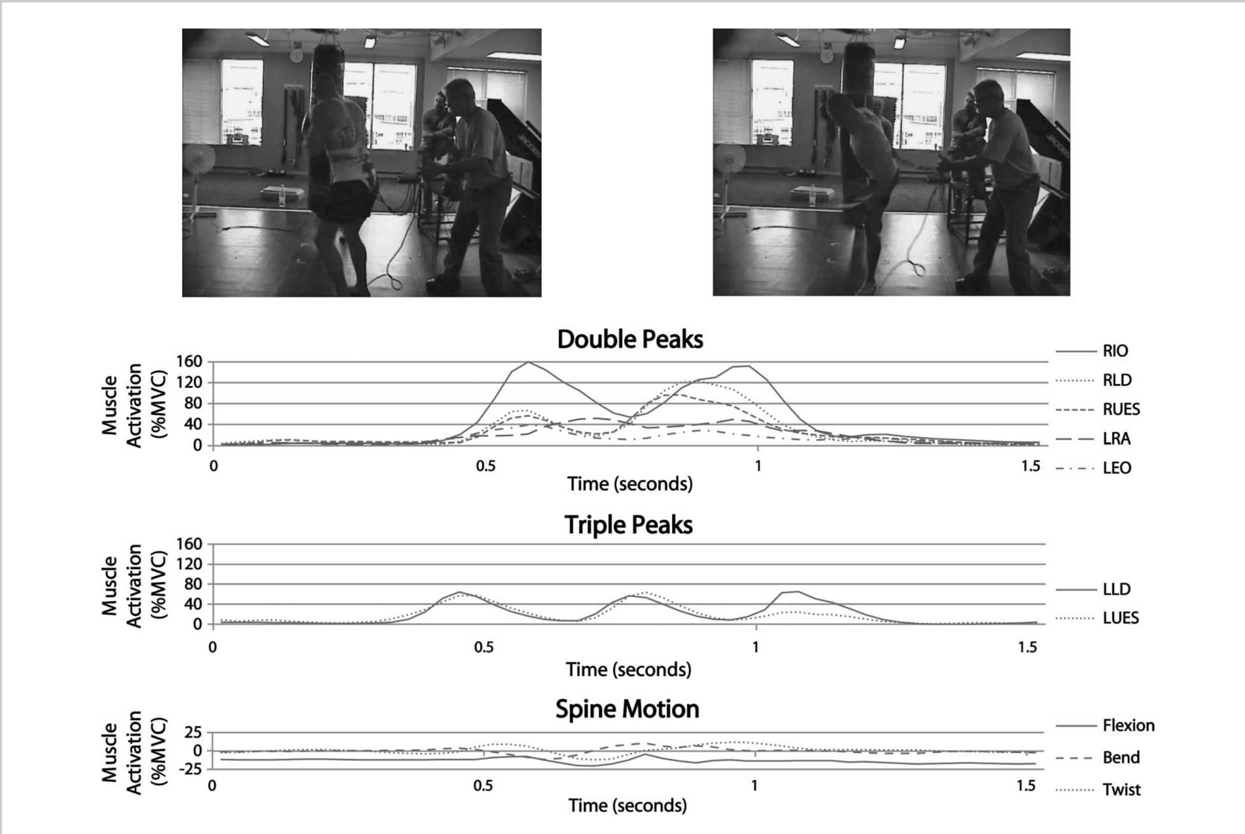

Figure 5. Side kick is a more complex motion, which created triple peak in less than 1 second in 2 muscles.

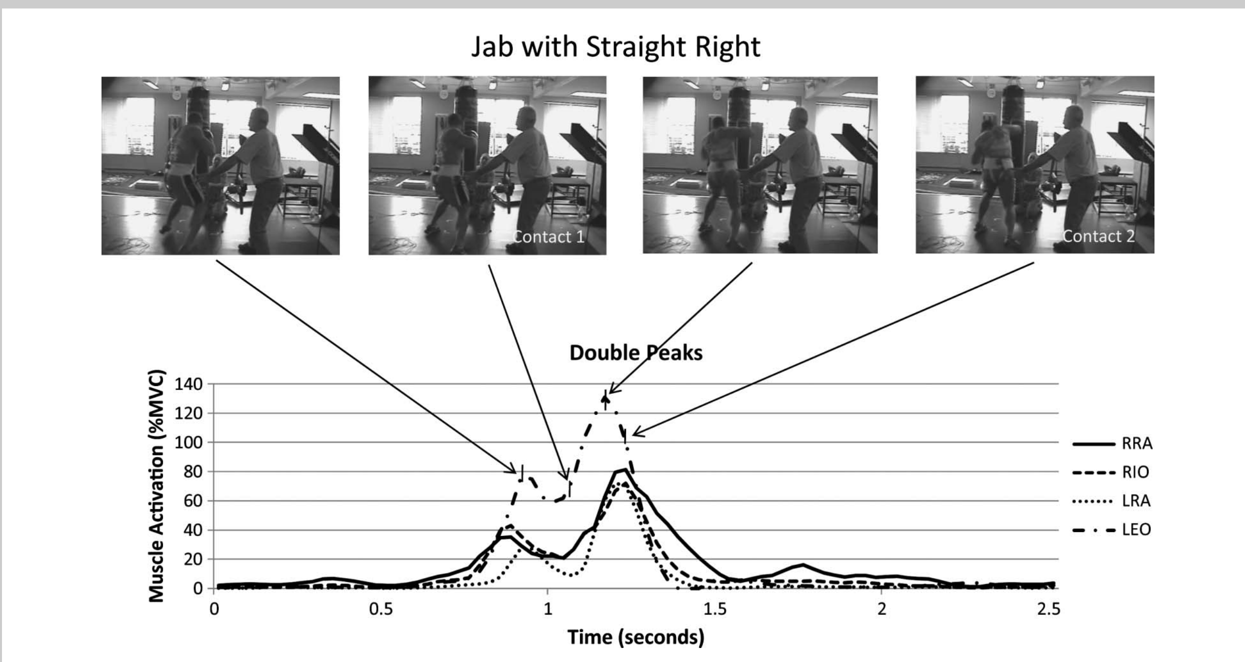

Figure 6. Jab followed with straight right strike forms a combination and double peak profile in abdominal wall.

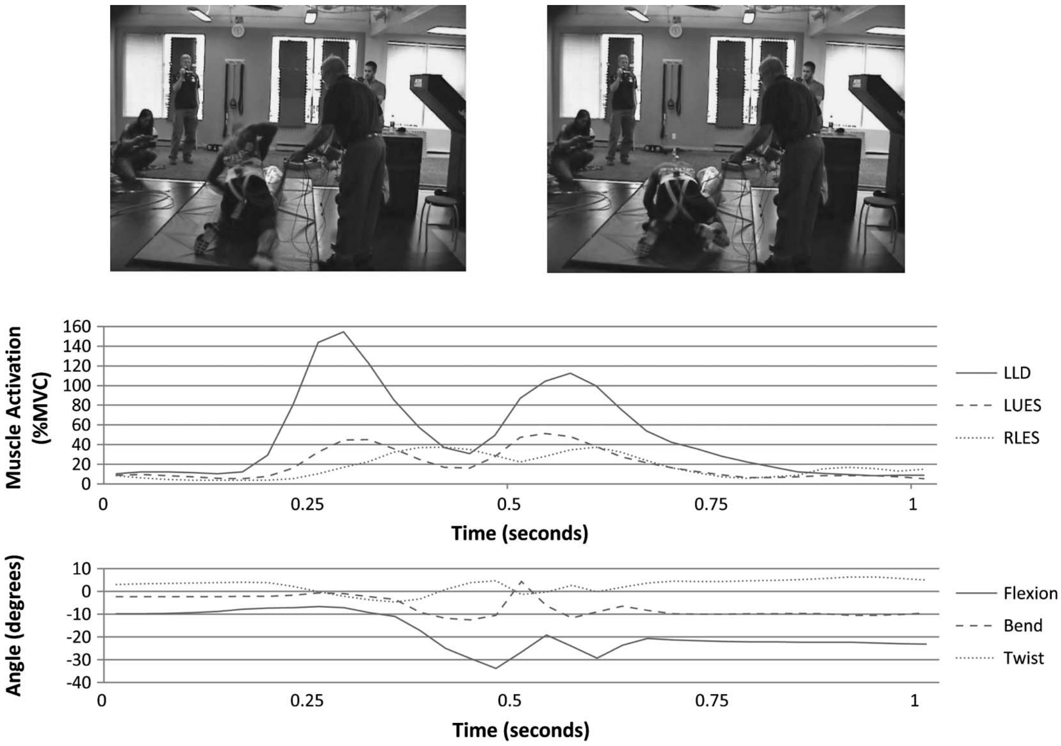

Figure 7. In "ground and pound" technique, very explosive hand and elbow strikes occur in less than .5 seconds.

activity was often associated with initiation of motion. As the hand or foot gained speed, a relaxation phase was sometimes observed followed by a second peak associated with the body stiffening at impact to create a harder impact.

Kicks created more distinct double peaked activation profiles. Each side kick elicited the double peak of the erector spinae. Even during bursts of multiple kicks, similar pulsing patterns of some muscles follow the double peak pattern, with some muscles involved in both peaks, whereas others are more involved with the initial peak and others with the second peak (Figure 3).

The spinning back kick is more complex given the leg kick combined with a whole body spinning motion. Still, the on/off pulses are seen in the muscles (Figure 4).

The stiffening double peak of the erector spinae and some abdominal muscle is seen in the side kick, the first peak presumably stiffening the body to initiate motion and the second stiffening to enhance the strike force (Figure 5). Interestingly, this elite fighter actually demonstrated a triple peak in the upper back muscles. This is a complex movement involving a spinning twist together with leg motion. Although the exact purpose of each peak remains speculative, the point is that they were rapidly created, highlighting the importance of the ability to contract and relax quickly.

Figure 6 shows the movement initiated with the first burst of muscle activity to stiffen the body, allowing propulsion of the left fist. However, the left jab is not intended to create large force but to act as a very quick distraction to set up the right hook that creates much higher impact force with the second peak of muscle activation. Double peaks are rarer during single punches than in combination punches. Typically, the second peak is associated with fist contact of the second, and more powerful, punch.

"Ground and pound" techniques are characterized by very explosive hand and elbow strikes initiated by the torso when the athlete is kneeling on top of an opponent on the ground (Figure 7). Even though most of the motion is about the shoulder joint, the same stiffening to initiate the motion and stiffen for the strike are evident in these very fast motions in which the actual motion is completed in 300 milliseconds. Note the EMG first peak occurred before the spine motion with the second peak occurring at the instant of strike.

Discussion

This descriptive study documented that some torso muscles appear to activate in a double pulse pattern in which the first pulse often occurs just before, or during, initiation of the first limb motion. The second pulse occurs very close to impact. Both of these pulses are thought to stiffen the body to buttress limb motion dynamics; this is known as enhancing the "effective mass" (12). The reaction of the accelerating limbs, either the arms for hand strikes or the legs for kicks, must be buttressed by an opposing force, which appears to be created by a stiff torso. Interestingly, the researchers sometimes noticed a distinct double pulse in the guttural vocalizations emitted by the athletes known as "kiai" or an "energy shout" in Japanese martial arts. When asked, a couple athletes stated they were imaging these 2 phases during training in an effort to increase both speed and strike force. There was no other EMG data that we were aware of to compare with the data of this study.

The practical implications of this study involve both mechanisms and possible training approaches. Interviewing a national champion kick boxer with a reputation for very fast and hard punches and kicks was very insightful in that he would have an "expert view." After showing him the data obtained from UFC fighters, he commented that in training he imagines a "double pulse" separated by a relaxed phase in his mind corresponding to the double pulse documented here. He then consciously tries to "speed up the tape" in his mind to strike faster and hit harder. Some martial arts masters clap their hands twice to try and coach a double pulse. This qualitative observation, combined with the EMG data of this study, suggests that the peak associated with impact is the result of intentional preparation rather than the result of impact. Clearly, the neural signal (the raw EMG) occurs before impact.

Observing elite fighters suggest that performance limiters not only include the rate of muscle contraction but also the rate of muscle relaxation to facilitate the relaxation phase between the 2 pulses. Matveyev (9) showed that elite athletes could have a muscle relaxation time of up to 8 times faster than nonathletes. The same work suggested that although relaxation rate is difficult to train, the release of an isometric contraction into full relaxation and speed of movement is the most effective training method. This principle is very appropriate for MMA athletes who transition from periods of isometric muscle contraction to explosive contraction/relaxation cycles. Josephson (6) noted that the rate of muscle relaxation becomes slower as muscle length increases because of an increase in the Ca^{2+} affinity of myofilaments with increasing muscle length. Although it is well known that fast twitch muscle fibers have a shorter relaxation time, it is interesting to consider training regimens that can alter fast and slow twitch metabolism. Caiozza (4) found that muscle that is predominately composed of the slow myosin heavy chain isoform has a longer relaxation period than that of one that was transformed to a fast muscle using hind limb unloading and hyperthyroidism intervention. Interestingly, Olympic weightlifters train explosively, and some avoid any form of aerobic work, even avoid walking up stairs, in an attempt to change fiber metabolism to fast twitch and speed up contraction and relaxation rates (10). However, such training approaches to increase relaxation time is not an option for MMA athletes, given the aerobic demand of the sport. On the other hand, apart from the neural determinants of muscle activation and relaxation rates, several physiologic factors are known to influence rates. These include (1) the duration of Ca^{2+} transient (release and uptake); (2) the affinity type (level) of troponin for Ca^{2+} ; and (3) the rate of cross-bridge detachment (14). These biological reactions are very temperature sensitive in that high temperature permits Ca^{2+} pumps to pump faster, resulting in muscles with faster rates of relaxation capable of operating at a higher frequency for a given volume (14). This would suggest that warm-up before performance may enhance the rate of contraction and relaxation.

Training to enhance contraction-relaxation times is intriguing. No studies exist to guide this other than the writing of Matveyev (9) as cited in Siff's work, *Supertraining* (15), which documents some of the obscure Soviet science. Training to enhance effective mass can follow several different approaches (e.g., McGill, 2009) (10) and is currently under scientific quantification by our research group.

This study only tested 5 participants but was the first to investigate elite MMA athletes using EMG, as far as we are aware. Not every strike demonstrated the "double pulse," nor are only elite MMA athletes capable of this feature. They simply constitute an interesting study group to document the phenomenon. However, we have observed similar "pulsing" of activation in other elite sportsmen, including golfers and sprinters (10). There is also the issue of "tuning" the EMG signal, which is the neural input to the muscle, to mimic the mechanical output of the muscle, which is force. Initially, a low-pass filter cut-off frequency of 2.5 was chosen to process the rectified EMG given that this value best represented the transfer function between the EMG and force in torso muscles (2), at least in ordinary young people. However, the choice of cut-off frequency effects the magnitude of the smoothed signal and also phase shifts the output signal to mimic the electromechanical delay. Given that the subjects were elite athletes, it is possible that they possessed a shorter electromechanical delay than "average" people, possibly affecting the conclusions. For this reason, the data were also processed at cut-off frequencies of 3.5 and 4.5 Hz. It is a possibility that the second pulse of muscle activity is not associated with stiffening to enhance the effective mass at impact but rather a pulse to return the foot or limb to the guard position. The result obtained using the higher cut-off frequencies resulted in a slightly smaller phase shift and shorter time of the pulse, but this does not change the conclusion that the second pulse was associated with impact. Having stated this, it is possible that a pulse to quickly return the foot or fist back to the ready posture may be an effective strategy to further enhance the effective mass of the body upon impact. Bruce Lee claimed that trying to reduce the contact time of the fist by pulling back into a guard position faster created a more forceful strike (8). This may have enhanced the effective mass. Finally, this descriptive study was designed as a series of case studies given the unique demands of the tasks and capabilities of the MMA athletes and not for statistical analysis.

Optimizing strike force and reducing the time taken for the hand or foot to reach the opponent requires paradoxical muscle variables. On one hand, muscle force propels the hand or foot, yet on the other, corresponding muscle stiffness slows the motion, suggesting that rapid relaxation may be helpful. Furthermore, upon contact, increasing the effective mass with muscle stiffness enhances the strike force. This appears to be accomplished by elite MMA athletes by producing a "double pulse" in some of their muscles. In this way, elite strike performance may be determined by a contraction-relaxation-contraction cycle. This suggests it may be fruitful to train rapid rate of relaxation together with rapid rate of contraction to enhance this form of speed strength.

Practical Applications

Evidence of contraction-relaxation-contraction pulses to achieve speed and strike force suggests that it may be helpful to train both rate of activation and rate of muscle relaxation. Some coaches purposefully attempt to train the pulses by beginning the movements and muscle activation patterns at a slow rate and then speeding up the technique. Others use pulsing drills that we are currently evaluating.

Acknowledgments

The authors thank the Natural Science and Engineering Research Council of Canada (NSERC) for their financial support and the UFC athletes who participated in this study.

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