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The effect of core training on distal limb performance during ballistic strike manoeuvres

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ABSTRACT

Ballistic limb motion is enabled by proximal "core" stiffness. However, controversy exists regarding the best method of training this characteristic. This study sought to determine the most effective core training method to enhance distal limb athleticism. A total of 12 participants (24 ± 3 years, 1.8 ± 0.05 m, 76.8 ± 9.7 kg) consisting of Muay Thai athletes performed a core training protocol (Isometric vs. Dynamic, with Control) for 6 weeks, using a repeated measures design to assess performance (peak strike velocity, peak impact force, muscular activation) in various strikes. Isometric training increased impact force in Jab (554.4 ± 70.1 N), Cross (1895.2 ± 203.1 N), Combo (616.8 ± 54.9 N), and Knee (1240.0 ± 89.1 N) trials ($P < 0.05$). Dynamic training increased strike velocity in Jab (1.3 ± 0.2 $m \cdot s^{-1}$), Cross (5.5 ± 0.9 $m \cdot s^{-1}$), Combo (0.7 ± 0.1, 2.8 ± 0.3 $m \cdot s^{-1}$), and Knee (3.2 ± 0.3 $m \cdot s^{-1}$) trials ($P < 0.05$). Isometric training increased Combo impact force 935.1 ± 100.3 N greater than Dynamic and 931.6 ± 108.5 N more than Control ($P < 0.05$). Dynamic training increased Jab strike velocity 1.3 ± 0.1 $m \cdot s^{-1}$ greater than Isometric and 0.8 ± 0.1 $m \cdot s^{-1}$ more than Control ($P < 0.05$). It appears that both static and dynamic approaches to core training are needed to enhance both velocity and force in distal limbs.

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KEYWORDS
Muay Thai; martial arts; performance; core stability; proximal stiffness; athleticism; spine

Introduction

Striking martial arts such as Muay Thai involve ballistic limb motion to deliver high impact force at maximal velocities to an intended target. For centuries, these athletes have sought out the most effective training methods to enhance their striking speed, impact force, and other markers of performance. The body is an articulated linkage where proximal stiffness and stability is necessary to enable rapid movements of distal segments (McGill, 2016). This mechanism requires the core musculature (muscles proximal to the ball and socket joints of the hips and shoulders) to prevent spine motion and buttress the torso, rather than generate movement akin to the musculature of the distal limb segments. In this way, the core muscles increased spinal stiffness and stability to prevent unwanted torso motion when exerting against external loads (Bergmark, 1987). Extending this concept to enhancement of athletic performance, an athlete must generate sufficient stiffness in the high mass torso for several reasons. First, proximal stiffness in the torso reduces small eccentric movements, representing a "giving way" or energy loss, to enhance distal limb motion velocity (McGill, 2014). Second, the spine is a flexible column that must be stiffened to enable it to bear more load without buckling (Bergmark, 1987). There is also evidence of rapid muscle activation/relaxation sequencing in high-performance athletes who seek more effective strikes with higher limb speed and higher contact force at the terminal end of the linkage (hands or feet) (McGill, 2014; McGill, Chaimberg, Frost, & Fenwick, 2010). When muscles contract, they create both – force and stiffness (Brown & McGill, 2009a). Hence, the speed strength paradox is formed where muscle force is needed in a pulse-like fashion to initiate limb speed followed with relaxation to decrease stiffness to enhance closing velocity between the hand and the target. Thus, it appears that an interplay between activation and relaxation, working to create both an inertial high mass torso with rapidly moving limb segments is a necessary condition of proficient striking performance. There has been little formal investigation into enhancement of these mechanisms. This study sought to determine the most effective core training method (between Isometric or Dynamic approaches) to enhance distal limb athletic performance (impact force and strike velocity).

Numerous investigations into the relationship between core stiffness/stability, training, and athletic performance have yielded varied results. Nesser, Huxel, Tincher, and Okada (2008) found weak correlations between Isometric core stability and strength, speed, and power in football players, and concluded that implementing core training protocols would not substantially enhance athletic performance. However, this investigation only correlated performance and endurance measures without examining if training core endurance affected performance. Taanila et al. (2009) showed improvements in military testing parameters, including sit-up endurance tests, after training with Isometric core exercises. Both Willardson (2007) and McGill (2014) have discussed the

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use of core stability exercise to enhance sport performance by buttressing the torso to facilitate distal limb motion. McGill et al. (2010) commented on the speed/strength and force/stiffness paradox after observing activation patterns termed as the “double peak” in elite mixed martial arts (MMA) athletes when striking. Muscles when activated create both, force and stiffness. But stiffness slows rapid motion so that pulse patterns of activation are needed to create high limb velocity. Specifically, a muscular pulse in the torso and limbs initiate limb movement. This is followed by a relaxation phase as the closing velocity of the hand/foot to the target increases. Elite athletes then produce a second impulse at impact to create a stiffened resulting in a larger “effective mass” and a higher strike force. Coaches refer to this as “getting the body behind the force” or “turning the body to stone”, so there is minimal energy loss. McGill (2014) reported a similar pulsing phenomenon in sprinters and golfers at impact. The idea of enhancing effective mass to heighten impact force was hypothesised by Blum (1977), Neto, Magini, and Saba (2007), and Pain and Challis (2002). Within the world of martial arts, research dating back to 1985 addressed performance differences between novice and elite boxers (Filimonov, Koptsev, Husyanov, & Nazarov, 1985). We were generally interested in training techniques to enhance elite strike performance. While there has been some work examining the role of strength and conditioning training to improve martial arts performance (Turner, 2009), we could not find data that assessed torso stiffness, limb speed, or strike effectiveness. Anecdotally, methods of training muscular relaxation have been used by martial artists (Little, 2001; Tsatsouline, 2006). However, the lack of investigation into which training exercises enhance strategic muscle pulses and core stiffness, and whether they actually enhance performance motivated this research. We chose a population of Muay Thai trained athletes given their athletic objectives of limb speed and strike force enhancement.

Isometric core exercises have been demonstrated to sufficiently create activation of the core musculature (Axler & McGill, 1997; Callaghan Gunning, & McGill, 1998; Kavcic, Grenier, & McGill, 2004; McGill & Karpowicz, 2009), while sparing the spine from excessive loads and injurious movement patterns. Dynamic “core exercises” have similarly been assessed for muscle activation patterns and in some cases joint loading (McGill, Cannon, & Anderson, 2014, McGill, Karpowicz, & Fenwick, 2009; McGill, Karpowicz, Fenwick, & Brown, 2009, McGill, Marshall, & Andersen, 2013; McGill, McDermott, & Fenwick, 2009). However, their ability to influence speed/force “striking” performance has not been assessed. Collectively, this large body of evidence suggests that core exercises influence stiffness and corresponding joint loading but the influence on speed/strength performance remains unknown. This study tested an approach that has been proven to enhance short-term stiffness in the torso (Lee & McGill, 2015) which to the authors’ knowledge, but the effect on athleticism remains unknown. The specific question was: What core training style is best suited to enhance strike force and speed of Muay Thai striking – an Isometric or Dynamic training approach? It was hypothesised that Dynamic core training would better improve strike speed than an Isometric approach or no (Control) training, while Isometric core training would enhance strike impact force better than a Dynamic approach or no (Control) training given existing evidence for enhancing “effective mass”.

Methods

Experimental approach to the problem

A repeated measures test/retest protocol was used to examine changes in biomechanical performance measures (impact force, strike velocity, and core and hip electromyography signals) after a 6-week core training protocol consisting of Isometric bracing or Dynamic movement exercises in 12 male Muay Thai athletes. All participants were recruited and trained between March 2013 and June 2013 during daytime hours. As physiological markers of health and performance were not within the scope of the study controls for nutrition and hydration were not used. Participants’ Muay Thai strike performance was measured before and after a 6-week training period (or waiting period for the Control group). After the initial data collection, participants were divided into an Isometric training group, Dynamic training group, or Control group. Isometric and Dynamic training groups performed a training programme progressing in intensity-based on static-bracing exercises and movement/speed-based exercises, respectively.

Participants

A total of 12 young healthy (24.2 ± 2.9 years, 1.8 ± 0.05 m, 76.8 ± 9.7 kg) were selected from a population of club Muay Thai fighters; a martial art native to Thailand involving standing striking with the fists, elbows, knees, and shins. Exclusion criteria consisted of any individuals who have experienced low back pain or injury currently or within the past year. Participants were trained in Muay Thai boxing for at least 1 year (range: 1.5–6 years of consistent training) with the majority (10) having competitive amateur records and 2 participants being provincial and international amateur champions in their respective weight classes.

All participant recruitment and data collection procedures were performed in accordance with University Office of Research Ethics guidelines. The participants were informed of the purpose and method of the study to ensure that they understood completely, and each provided written informed consent to participate. Participants were also informed that at any time during the data collection or training protocol they were free to withdraw from the study. Written informed consent was gained in agreement with University guidelines.

Procedures

Muay Thai strike performance was assessed using strike impact force strike velocity and electromyography signals. All 3 were measured during 4 trials of Muay Thai strikes, described below, before, and after a 6-week intervention of core training or rest. The training intervention consisted of 3 groups, each with 4 participants; 1 group performed Isometric core exercises, 1 group performed Dynamic core exercises and the Control group performed no special exercises during this period.

Strike trials

The martial art of Muay Thai involves 2 competitors striking at each other while standing using points of their fists, elbows, knees, and shins. To gather information regarding the efficacy of these strikes, 4 trials were selected typical to strikes used in Muay Thai training and competition. All strikes were performed from the participant's dominant stance in which a right-handed participant would stand with their left leg and arm in front and right leg behind them, in a shoulder width stance; and vice versa for a left-handed participant. The 4 trials used were a Jab (lead hand strike with the fist), Cross (rear hand strike with the fist), Knee (rear leg strike impacting with the tip of the knee), and Jab–Cross combination (aka "Combo", a Jab followed in succession by a Cross), as illustrated in Figure 1. Three repetitions of each trial were performed in a randomised order as to eliminate any bias or learning effect, with 1–2 min of rest between each trial to reduce peripheral fatigue between trials. Researchers also confirmed before each trial that the participant was adequately rested and ready to perform.

Instrumentation

Electromyography (EMG) signals, whole body kinematics, and strike force were collected during strike trials. Data sources were connected to Vicon MX Ultranet hardware (Vicon MX, Vicon Motion Systems, Oxford, UK) and synchronised during data collection using Vicon Nexus 1.8 software (Vicon MX, Vicon Motion Systems, Oxford, UK). All signals were collected at various frequencies and down-sampled to 60 Hz during post-processing.

Figure 1. Examples of each of the strikes tested pre/post-core training. (a) Jab, (b) Cross, (c) Jab–Cross Combination ("Combo"), (d) Knee.

Electromyography

EMG signals were collected on bilateral core and hip musculature using pre-gelled, disposable, monopolar Ag–Cl disc-shaped surface electrodes (30 mm diameter, Medi-traceTM 100 Series Foam Electrodes, Covidien, MA, USA) placed on the skin over each muscle of interest (rectus abdominis [RA], external oblique [EO], internal oblique [IO], latissimus dorsi [LD], upper erector spinae [UES], lower erector spinae [LES], gluteus maximum [GMax], gluteus medius [GMed]). Briefly, normalised signals were obtained as follows. Signals were amplified (±2.5 V; AMT-8, Bortec, Calgary, Canada; bandwidth 10–1000 Hz, common mode rejection ratio (CMRR) = 115 db at 60 Hz, input impedance = 10 GX) and sampled at 2048 Hz, low-pass filtered with a 500 Hz, rectified and low-pass filtered at 2.5 Hz (single pass second order) to mimic the frequency response of torso muscle after Brereton and McGill (1998) and normalised to the maximum voltage produced during maximum voluntary contraction (MVC) trials to produce a linear envelope mimicking the muscle force output; a technique used many times before [5]. Maximum effort to elicit maximum neural drive was the goal of the MVC trials. MVC's were obtained using 4 postures: (1) a modified sit-up position in which participants isometrically attempted to produce trunk flexion, side bend, and twist motions against resistance, (2) Isometric trunk extension while cantilevered in a prone position over the edge of a table (Biering-Sorensen position) against external resistance, (3) Isometric wide grip pull-up posture in which the participant attempted to isometrically pull against a horizontal bar while being resisted with instructions of maintaining a maximally tight grip and attempting to "bend the bar" while pulling vertically, and (4) side lying abduction position where participants lay on 1 side and attempted to produce hip abduction against resistance. All EMG signals were normalised to a per cent MVC which allowed day-to-day comparisons of muscle activation amplitude with maximal values of the enveloped signal reported.

Limb kinematics

Three-dimensional (3D) whole body kinematics were recorded using an infrared motion analysis system (Vicon MX, Vicon Motion Systems, Oxford, UK) using an 8 camera set-up sampled at 60 Hz. Rigid clusters were attached on the thorax, pelvis, upper arms, forearms, hands, thighs, shanks, and feet; each cluster with 4 reflective markers except the thighs, containing 5 markers. Jab, Cross, and Jab–Cross limb velocities were measured from the displacement of the striking hand's cluster. The location of the hand cluster was calculated by taking the average of the 3D location coordinates 4 markers. Velocity was then calculated using a numerical differentiation of each coordinate, as per the following equations:

$$V_x = \frac{X_2 - X_1}{t_2 - t_1} \tag{1}$$

$$V_y = \frac{Y_2 - Y_1}{t_2 - t_1} \tag{2}$$

$$V_z = \frac{Z_2 - Z_1}{t_2 - t_1}. \tag{3}$$

Velocities about each axis were then normalised to a scalar magnitude using the equation:

$$V_{limb} = \sqrt{V_x^2 + V_y^2 + V_z^2}. \tag{4}$$

Strike force

A portable "pancake" force transducer designed for impact use (AMTI, Massachusetts, USA) was mounted to a fixed surface to record strike force. A steel cylinder was mounted to the transducer with a padded body protector, typically worn to protect boxing trainers from strikes to the body, wrapped around the circumference to act as a target. As all strikes across all participants were measured in this manner, the damping effect of the body protector was not accounted for in impact force measurements. Impact data were sampled at 2160 Hz and filtered with a second-order dual pass Butterworth filter with cut-off frequency of 100 Hz. Cut-off frequency was determined using a fast Fourier transformation; filtering, processing, and analysis were performed via MATLAB software (Version r2012a; The MathWorks Inc., Natick, Massachusetts, USA).

Core training protocols

Participants trained for 6 weeks using either Isometric or Dynamic core exercises (the Control group did not train). All participants were asked to refrain from performing any core exercises outside of those assigned by researchers during the study. The Isometric training group performed static exercises designed to challenge the core musculature via bracing cues. The Dynamic training group performed exercises based on torso movement. Both training programmes were matched for volume and intensity and periodised to increase challenge every 2 weeks, dividing each programme into 3 phases (Tables 1 and 2 for a description of the progressive programmes).

Statistical analyses

Statistical tests were performed using IBM® SPSS® Statistical software (Version 19, IBM Corporation, Somers, New York, USA). 3 × 2 repeated measures analysis of variance (ANOVA) (3 groups, before and after training) was conducted for comparing peak impact force peak EMG amplitudes, and peak strike velocity; within and between training groups. Where applicable, post hoc analyses were performed using the Tukey honest significant difference (HSD) test when a significant effect was detected with statistical significance set at $P \leq 0.05$.

Results

Impact force, strike velocity, and torso and gluteal EMG were measured before and after a 6-week bout in the 3 groups: Isometric, Dynamic, or no core training (Control group).

Table 1. Isometric training protocol.

Exercise	Sets × Reps	Freq	Sets × Reps	Freq	Comments
	Week 1		**Week 2**		
Plank	5,4,3,2,1 × 10 s	4× per week	5,4,3,2,1 × 10 s	7× per week	Focus on quality of core contraction and postural cues. Descending pyramid sets (Start at 5 reps at 10 s each, next set decrease 1 rep, continue to decease 1 rep per set)
Bird dog	5,4,3,2,110 s	4× per week	5,4,3,2,1 × 10 s per side	7× per week	
Side bridge	5,4,3,2,1 × 10 s	4× per week	5,4,3,2,1 × 10 s per side	7× per week	
Torsional buttress			5,4,3,2,1 × 10 s per side	7× per week	Focus on quality of core contraction and postural cues. Use a hold time before shaking begins, maximum 10 s
	Week 3		**Week 4**		
Anterior pallof press	5,4,3,2,1 × 10 s	4× per week	Same volume, increase load	4× per week	Focus on quality of core contraction and postural cues
Posterior pallof press	5,4,3,2,1 × 10 s	4× per week	Same volume, increase load	4× per week	
Suitcase hold	5,4,3,2,1 × 10 s per side	4× per week	Same volume, increase load	4× per week	
Anti-rotation pallof press	5,4,3,2,1 × 10 s per side	4× per week	Same volume, increase load	4× per week	
	Week 5		**Week 6**		
Stir the pot	5×10 s per direction	4× per week	5×10 s per direction	4× per week	Begin on knees, progress to toes. If 10 s are not feasible, train below and progress through the phase
Inverted row	Up to 5×10	4× per week	5×10	4× per week	If 10 reps are not feasible, perform as many reps as possible and maintain static posture. Focus on keeping torso straight (avoid hip hiking/sagging)
Kettlebell unilateral rack walk	3×30 m walk per side	4× per week	Same volume, increase load	4× per week	Focus on core contraction and upright posture (avoid lateral lean)
Half kneeling woodchop	Up to 5×10 per side	4× per week	5×10 per side	4× per week	If 10 reps are not possible, perform as many reps as possible and progress through the phase.

Table 2. Dynamic training protocol.

Exercise	Sets × Reps	Freq	Sets × Reps	Freq	Comments
	Week 1		**Week 2**		
Curl up	Up to 5×10	4× per week	Up to 5×10	7× per week	Focus on quality of muscular contraction; visualise muscular activation throughout motion. A total of 10 repetitions per set with sets performed until marked muscular fatigue sets in (up to 5 sets)
Superman	Up to 5×10	4× per week	Up to 5×10	7× per week	
Side curl up	Up to 5×10 per side	4× per week	Up to 5×10 per side	7× per week	
Twisting curl up	Up to 5×10 per side	4× per week	Up to 5×10 per side	7× per week	
	Week 3		**Week 4**		
Advanced curl up (limbs extended)	Up to 5×5–10	4× per week	Up to 5×5–10	4× per week	Begin with 5 × 5 and progress repetitions to 10. If 10 reps per side are too easy add/ increase weight
Back extension	Up to 5×5–10	4× per week	Up to 5×5–10	4× per week	
Russian barbell twist	Up to 5×5–10 per side	4× per week	Up to 5×5–10 per side	4× per week	
	Week 5		**Week 6**		
Curl up twitch	Up to 5×5–10	4× per week	Up to 5×5-10	4× per week	Begin unweighted and focus on twitch speed and rate of activation/relaxation. Begin with 5×5 and progress repetitions to 10. If 10 reps per side are too easy, add/increase weight
Superman twitch	Up to 5×5–10	4× per week	Up to 5×5–10	4× per week	
Lateral medball throw	Up to 5×5-10 per side	4× per week	Up to 5×5-10 per side	4× per week	Ball velocity comes from torso movement, not arms. Begin with 5×5 and progress repetitions to 10. If 10 reps per side are too easy, add/increase weight
Rotational medball throw	Up to 5×5-10 per side	4× per week	Up to 5×5-10 per side	4× per week	Ball velocity comes from torso movement, not arms. Begin with 5×5 and progress repetitions to 10. If 10 reps per side are too easy, add/increase weight

Impact force

Isometric and Dynamic trainings increased impact force in almost all strike trials. Jab impact force increased by 17.9% after Isometric training (2539.3 ± 89.1–3093.7 ± 69.4 N) ($F(1,3) = 70.8$, $P < 0.001$, $\beta = 1.0$), and by 18.3% after Dynamic training (2614.7 ± 493.1–3199.6 ± 437.9 N) ($F(1,3) = 34.1$, $P = 0.01$, $\beta = 0.9$). Knee impact force increased by 13.1% after Isometric training (8242 ± 132.3–9482 ± 152.8 N) ($F(1,3) = 16.2$, $P = 0.03$, $\beta = 0.8$), compared with a 7.1% increase after Dynamic training ($F(1,3) = 10.3$, $P = 0.05$, $\beta = 0.7$). Cross impact force increased by 27% after Isometric training (5008.6 ± 76.3–5008.6 ± 76.3 N) ($F(1,3) = 73.4$, $P < 0.001$, $\beta = 1.0$) but Dynamic training did not elicit any significant increases or decreases. The Control group did not experience any significant changes in impact force.

Comparing between training groups, Isometric training increased impact force more than Dynamic training for Cross, Combo, and Knee trials, and was superior to the Control group for all strike trials. Dynamic training yielded greater effects in increasing impact force than the Control group for Jab and Knee trials, but was not more effective than the Isometric group for any trials. The Control group did not show any effects in increasing impact force more than Isometric or Dynamic training. Isometric training increased Cross impact force by 1895.2 ± 155.2 N, compared with a 232.2 ± 30.9 N decrease after Dynamic training ($F(1,6) = 36.5$, $P < 0.001$, $\beta = 0.8$) and 229.5 ± 40.1 N decrease after Control ($F(1,6) = 40.1$, $P < 0.001$, $\beta = 0.8$). Similarly, Isometric training increased Knee impact force by 1240.0 ± 143.2 N, while after Dynamic training Knee impact force decreased by 660.3 ± 101.8 N ($F(1,6) = 6.9$, $P = 0.04$, $\beta = 0.7$) and 299.7 ± 41.5 N decrease after Control ($F(1,6) = 44.5$, $P < 0.001$, $\beta = 1.0$).

These results are summarised in Tables 3 and 4, and Figure 2.

Strike velocity

Isometric and Dynamic trainings both increased peak limb velocity for almost all strike trials. Peak strike velocity increased within the Isometric training group during Cross trials by 23.9% (6.7 ± 0.7–8.8 ± 0.9 $m \cdot s^{-1}$) ($F(1,3) = 34.3$, $P = 0.01$, $\beta = 0.8$) and the second strike of Combo trials by 5.2% (7.1 ± 0.5–9.0 ± 1.0 $m \cdot s^{-1}$) ($F(1,3) = 16.5$, $P = 0.03$, $\beta = 0.7$). Dynamic training increased peak strike velocity for Jab trials by 22.4% (4.5 ± .4–5.8 ± .6 $m \cdot s^{-1}$) ($F(1,3) = 103.2$, $P = 0.006$, $\beta = 0.9$), Cross trials by 45.5% (6.6 ± 0.9–12.1 ± 1.3 $m \cdot s^{-1}$) ($F(1,3) = 140.9$, $P < 0.001$, $\beta = 1.0$), Combo trials by 13.2% (7.6 ± 0.8–10.4 ± 1.0 $m \cdot s^{-1}$) ($F(1,3) = 34.7$, $P = 0.01$, $\beta = 0.8$), and Knee trials by 29.1% (7.8 ± 0.6–11.0 ± 1.0 $m \cdot s^{-1}$) ($F(1,3) = 12.6$, $P = 0.04$, $\beta = 0.7$). No changes were measured within the Control group.

Comparing between training groups, Isometric training had a greater effect on increasing strike velocity than Control for Cross, Combo, and Knee trials ($P < 0.05$ for al trials), but did not increase strike velocity more than Dynamic training during any trials. Isometric training increased strike velocity during Cross trials by 2.1 ± 0.3 $m \cdot s^{-1}$ compared with a 0.3 ± 0.1 $m \cdot s^{-1}$ increase after Control ($F(1,6) = 13.9$, $P = 0.01$, $\beta = 0.8$), and increased the first and second strikes of the Combo trials by 0.3 ± 0.04 and 1.9 ± 0.1 $m \cdot s^{-1}$ increase, respectively, compared with a 0.6 ± 0.1 and 0.5 ± 0.05 $m \cdot s^{-1}$ decrease after Control ($F(1,6) = 9.0$, $P = 0.03$, $\beta = 0.8$; $F(1,6) = 8.5$, $P = 0.03$, $\beta = 0.7$). Isometric training also increased Knee strike velocity by 1.2 ± 0.1 $m \cdot s^{-1}$ compared with a 0.4 ± 0.05 $m \cdot s^{-1}$ increase after Control ($F(1,6) = 9.8$, $P = 0.02$, $\beta = 0.8$). Dynamic training had a greater effect on increasing strike velocity compared with Isometric training and Control for all trials. Jab velocity increased by 1.3 ± 0.1 $m \cdot s^{-1}$ after Dynamic training, compared with a 0.0 ± 0.04 $m \cdot s^{-1}$ change after Isometric training

Table 3. Detailed statistics for impact force within each training group.

Trial		Stats (*F*-value, *P*-value, power): Isometric		Dynamic		Control	
Jab	Pre Post	$F(1,3) = 70.8$, $P < 0.001$, power = 1.0		$F(1,3) = 34.1$, $P = 0.01$, power = 0.9		$F(1,3) = 5.1$, $P > 0.05$, power = 0.2	
Cross	Pre Post	$F(1,3) = 73.4$, $P < 0.001$, power = 1.0		$F(1,3) = 2.6$, $P > 0.05$, power = 0.1		$F(1,3) = 4.9$, $P > 0.05$, power = 0.2	
Combo	Pre Post	$F(1,3) = 8.04$, $P > 0.05$, power = 0.4	$F(1,3) = 10.2$, $P = 0.05$, power = 0.7	$F(1,3) = 2.0$, $P > 0.05$, power = 0.1	$F(1,3) = 2.3$, $P > 0.05$, power = 0.1	$F(1,3) = 5.2$, $P > 0.05$, power = 0.2	$F(1,3) = 2.5$, $P > 0.05$, power = 0.1
Knee	Pre Post	$F(1,3) = 16.2$, $P = 0.03$, power = 0.8		$F(1,3) = 10.3$, $P = 0.05$, power = 0.7		$F(1,3) = 2.4$, $P > 0.05$, power = 0.1	

Table 4. Detailed statistics for impact force between each training group.

Trial		Stats (*F*-value, *P*-value, power): Iso/Dyn		Dyn/Con		Iso/Con	
Jab	Pre Post	$F(1,6) = 8.2$, $P = 0.03$, power = 0.7		$F(1,6) = 6.1$, $P = 0.05$, power = 0.7		$F(1,6) = 0.3$, $P > 0.05$, power = 0.07	
Cross	Pre Post	$F(1,6) = 36.5$, $P < 0.001$, power = 0.8		$F(1,6) = 0.3$, $P > 0.05$, power = 0.07		$F(1,6) = 40.1$, $P < 0.001$, power = 0.8	
Combo	Pre Post	$F(1,6) = 3.8$, $P > 0.05$, power = 0.2	$F(1,6) = 44.4$, $P < 0.001$, power = 0.8	$F(1,6) = 2.4$, $P > 0.05$, power = 0.3	$F(1,6) = 0.4$, $P > 0.05$, power = 0.1	$F(1,6) = 1.9$, $P < 0.05$ power = 0.2	$F(1,6) = 41.2$, $P < 0.001$, power = 0.9
Knee	Pre Post	$F(1,6) = 6.9$, $P = 0.04$, power = 0.7		$F(1,6) = 6.0$, $P = 0.05$, power = 0.7		$F(1,6) = 44.5$, $P < 0.001$, power = 1.0	

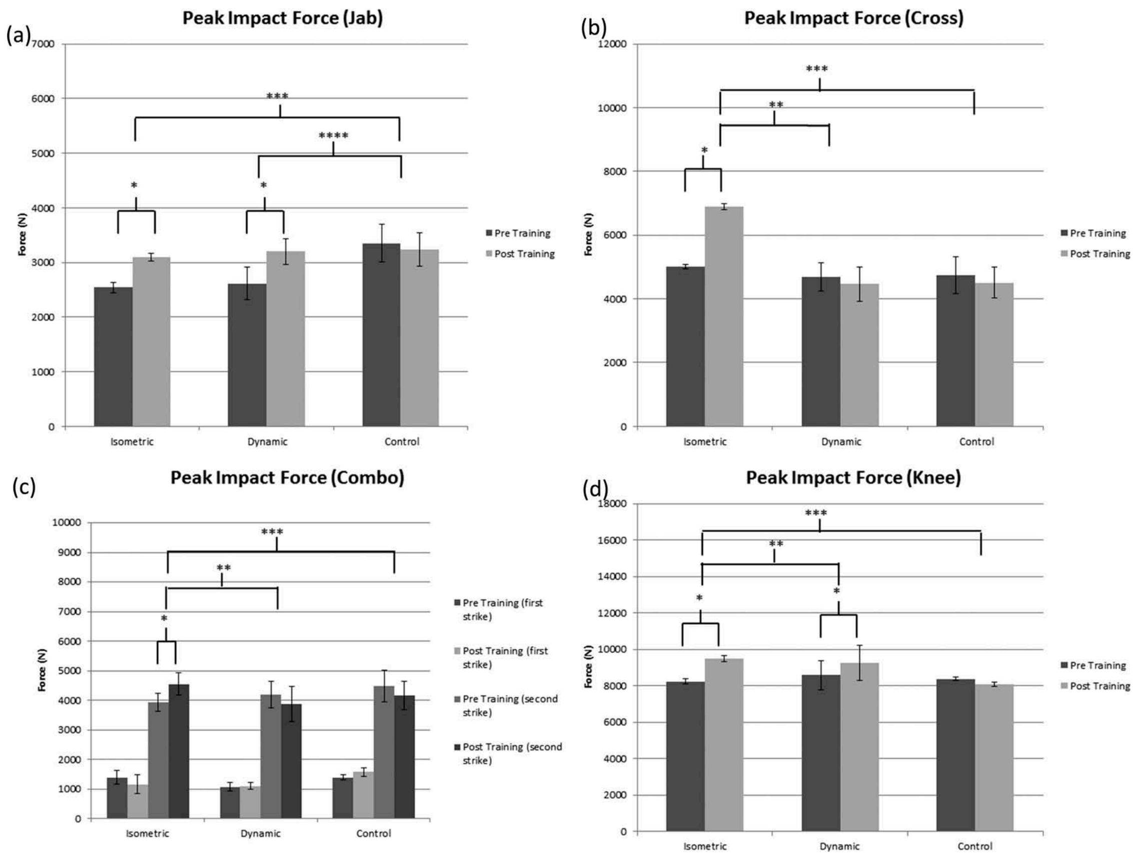

Figure 2. Peak impact force during (a) Jab, (b) Cross, (c) Jab–Cross Combination ("Combo"), (d) Knee strikes.
* – statistically significant ($P < 0.05$) difference within training group. ** – statistically significant ($P < 0.05$) difference between Isometric and Dynamic training groups. *** – statistically significant ($P < 0.05$) difference between Isometric and Control training groups. **** – statistically significant ($P < 0.05$) difference between Dynamic and Control training groups.

($F(1,6) = 34.2$, $P < 0.001$, $\beta = 1.0$) and 0.5 ± 0.05 $m \cdot s^{-1}$ increase after Control ($F(1,6) = 8.7$, $P = 0.03$, $\beta = 0.7$). During Cross trials, Dynamic training increased strike velocity more than Isometric training (5.5 ± 0.6 $m \cdot s^{-1}$ increase compared with a 2.1 ± 0.3 $m \cdot s^{-1}$ increase, respectively) ($F(1,6) = 6.0$, $P = 0.05$, $\beta = 0.7$), and Control (0.3 ± 0.05 $m \cdot s^{-1}$ increase after Control) ($F(1,6) = 18.3$, $P = 0.008$, $\beta = 0.9$). Dynamic training increased Combo velocity by 0.7 ± 0.08 and 2.8 ± 0.2 $m \cdot s^{-1}$ for the first and second strikes, respectively, compared with Isometric training which increased velocity by 0.3 ± 0.05 and 1.9 ± 0.2 $m \cdot s^{-1}$, respectively ($F(1,6) = 6.1$, $P = 0.05$, $\beta = 0.7$; $F(1,6) = 6.3$, $P = 0.05$, $\beta = 0.7$), and Control where strike velocity decreased by 0.6 ± 0.1 and 0.5 ± 0.05 $m \cdot s^{-1}$ ($F(1,6) = 14.3$, $P < 0.01$, $\beta = 0.8$; $F(1,6) = 69.6$, $P < 0.001$, $\beta = 1.0$). Knee velocity increased by 3.2 ± 0.3 $m \cdot s^{-1}$ after Dynamic training compared with a 1.2 ± 0.2 $m \cdot s^{-1}$ increase after Isometric training, and a 0.4 ± 0.1 $m \cdot s^{-1}$ increase after Control ($F(1,6) = 13.9$, $P = 0.009$, $\beta = 0.9$). The Control group did not significantly increase in strike velocity more than Isometric or Dynamic training.

These results are summarised in Tables 5 and 6, and Figure 3.

Electromyography

Significant increases in peak EMG amplitudes were measured within both Isometric and Dynamic training groups for all trials. During Jab trials, Isometric training elicited a 37% increase in EMG amplitudes across all musculature on average,

Table 5. Detailed statistics for strike velocity within each training group.

Trial		Stats (*P*-value, *F*-value, power): Isometric		Dynamic		Control	
Jab	Pre Post	$F(1,3) = 0$, $P > 0.05$, power = 0		$F(1,3) = 103.2$, $P = 0.006$, power = 0.9		$F(1,3) = 0.4$, $P > 0.05$, power = 0.07	
Cross	Pre Post	$F(1,3) = 34.3$, $P = 0.01$, power = 0.8		$F(1,3) = 140.9$, $P < 0.001$, power = 1.0		$F(1,3) = 0.4$, $P > 0.05$, power = 0.07	
Combo	Pre Post	$F(1,3) = 4.4$, $P > 0.05$, power = 0.4	$F(1,3) = 16.5$, $P = 0.03$, power = 0.7	$F(1,3) = 10.6$, $P = 0.05$, power = 0.7	$F(1,3) = 34.7$, $P = 0.01$, power = 0.8	$F(1,3) = 0.3$, $P > 0.05$, power = 0.06	$F(1,3) = 1.0$, $P > 0.05$, power = 0.09
Knee	Pre Post	$F(1,3) = 15.8$, $P = 0.03$, power = 0.7		$F(1,3) = 12.6$, $P = 0.04$		$F(1,3) = 1.2$, $P > 0.05$, power = 0.1	

Table 6. Detailed statistics for strike velocity between each training group.

Trial		Stats (*P*-value, *F*-value, power)		
		Iso/Dyn	Dyn/Con	Iso/Con
Jab	Pre Post	F(1,6) = 34.2, *P* < 0.001, power = 1.0	F(1,6) = 8.7, *P* = 0.03, power = 0.7	F(1,6) = 3.5, *P* > 0.05, power = 0.5
Cross	Pre Post	F(1,6) = 6.0, *P* = 0.05, power = 0.7	F(1,6) = 18.3, *P* = 0.008, power = 0.9	F(1,6) = 13.9, *P* = 0.01, power = 0.8
Combo	Pre Post	F(1,6) = 6.1, *P* = 0.05, power = 0.7 F(1,6) = 6.3, *P* = 0.05, power = 0.7	F(1,6) = 14.3, *P* < 0.01, power = 0.8 F(1,6) = 69.6, *P* < 0.001, power = 1.0	F(1,6) = 9.0, *P* = 0.03, power = 0.8 F(1,6) = 8.5, *P* = 0.03, power = 0.7
Knee	Pre Post	F(1,6) = 6.0, *P* = 0.05, power = 0.7	F(1,6) = 13.9, *P* = 0.009, power = 0.9	F(1,6) = 9.8, *P* = 0.02, power = 0.8

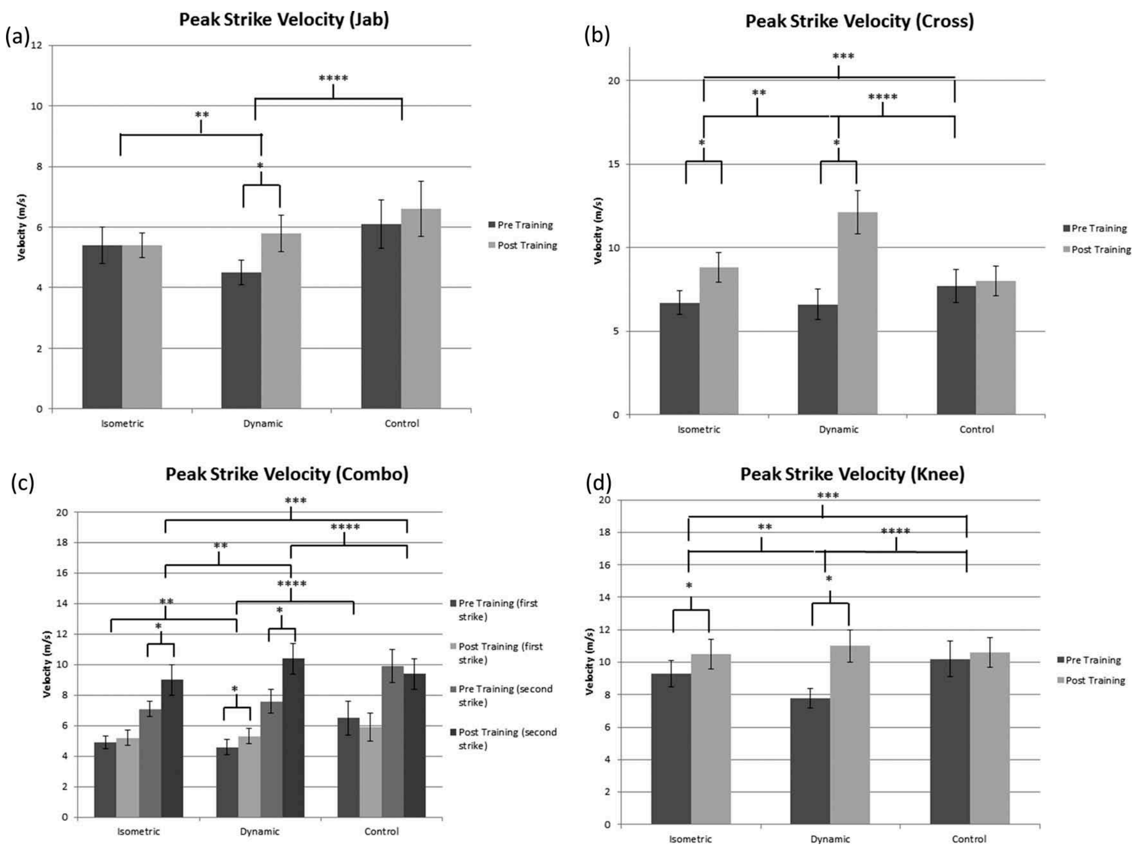

Figure 3. Peak strike velocity during (a) Jab, (b) Cross, (c) Jab–Cross Combination ("Combo"), (d) Knee strikes.
* – statistically significant ($P < 0.05$) difference within training group. ** – statistically significant ($P < 0.05$) difference between Isometric and Dynamic training groups. *** – statistically significant ($P < 0.05$) difference between Isometric and Control training groups. **** – statistically significant ($P < 0.05$) difference between Dynamic and Control training groups.

with the largest increases (range: 50–72%) in the left back (LLAT, LUES, LLES) and left abdominal (LRA, LIO) musculature (F(1,3) = 10.2–120.5, P = 0.001–0.5, β = 0.7–1.0). In comparison, Dynamic training elicited a 35% average increase in overall EMG signal during Jab trials, with the largest increases in the left and right abdominal musculature (LRA, LEO, LIO, RRA, REO, RIO; range: 30–69%) (F(1,3) = 11.5–140.1, P = 0.001–0.04, β = 0.7–1.0). Isometric training increased EMG amplitudes by 34% during Cross trials, with the largest increases (range: 30–60%) occurring in the right back (RLAT, RUES, RLES) and abdominal (REO, RIO) musculature (F(1,3) = 10.9–64.9, P = 0.001–0.05, β = 0.7–1.0). Dynamic training also increased EMG amplitudes on average by 35%, with the greatest increases (range: 36–58%) in the right back (RLAT, RUES, RLES) and gluteal (RGMax, RGMed) musculature (F(1,3) = 15.8–34.0, P = 0.01–0.03, β = 0.7–0.9). Combo trials experienced a 17% average increase in EMG amplitudes after Isometric training, and 23% average increase after Dynamic training. Isometric training yielded the greatest increases (range: 18–39%) in the right abdominal (RRA, REO, RIO) and gluteal (RGMed) musculature (F(1,3) = 10.4–34.1, P = 0.01–0.05, β = 0.7–0.9). Dynamic training had the greatest effect (range: 26–40%) on right abdominal (RRA, REO, RIO) and gluteal (RGMax, RGMed) musculature (F(1,3) = 16.4–103.9, P = 0.005–0.03, β = 0.7–0.9). Knee trials experienced a 25% average increase in EMG amplitudes after Isometric training, compared with a 20% increase after Dynamic training. Isometric training had the greatest effect (range: 24–36%) on the left and right abdominal (LEO, LIO, RRA, LEO, RIO) and right gluteal (RGMax, RGMed) musculature (F(1,3) = 10.1–72.8, P = 0.001–0.05, β = 0.7–1.0), while Dynamic training had the greatest effect (range: 10–42%) on right abdominal (RRA, REO, RIO) and gluteal (RGMax, RGMed) musculature (F(1,3) = 14.5–84.3, *P* = 0.001–0.01 β = 0.8–1.0).

Comparing between training groups, Isometric and Dynamic trainings increased peak EMG amplitudes more than Control for almost all musculature in all trials but comparisons between Isometric and Dynamic trainings revealed that some muscles responded more to Isometric training, while other muscles responded greater to Dynamic training. During Jab trials, Isometric training increased overall peak EMG amplitudes similarly to that of Dynamic training (37% vs. 35%) but left back (LLAT, LLES), left abdominal (LRA, LIO), RLES, RIO, and RGMed musculature experienced greater increases than with Dynamic training (F(1,6) = 6.3–40.8, *P* = 0.001–0.05, β = 0.7–0.8). Dynamic training had a greater effect than Isometric training for left gluteal (LGMax, LGMed), RUES, and RRA musculature (F(1,6) = 9.3–34.2, *P* = 0.001–0.02, β = 0.8–1.0). Isometric training increased overall peak EMG amplitudes by 103% more than Control on average, with significant increases in left back (LLAT, LLES), left abdominal (LRA, LIO), LGMed, right back (RUES, RLES), right abdominal (RRA, REO, RIO), and RGMed musculature (F(1,6) = 6.0–13.8, *P* = 0.01–0.05, β = 0.7–0.8). Dynamic training also increased overall peak EMG amplitudes more than Control, on average 103% more, with left back (LLAT, LLES), left abdominal (LRA, LIO), left gluteal (LGMax, LGMed), and right back, abdominal, and gluteal (RUES, RRA, REO, RIO, RGMed) musculature experiencing the greatest changes (F(1,6) = 8.1–36.9, *P* = 0.001–0.03, β = 0.8–0.9).

During Cross trials, Isometric and Dynamic trainings yielded similar responses in EMG amplitude (34% vs. 35% overall average increase). Isometric training increased peak EMG amplitudes greater than Dynamic training for left back and gluteal (LLES, LGMax), right abdominal (REO, RIO), and right gluteal (RGMax, RGMed) musculature (F(1,6) = 6.6–49.1, *P* = 0.001–0.05, β = 0.7–1.0); while Dynamic training had a greater effect in left back (LLAT, LUES), left abdominal (LRA, LEO), and right back and abdominal (RLAT, RUES, RLES, RRA) musculature (F(1,6) = 9.0–50.1, *P* = 0.001–0.03, β = 0.8–1.0). Isometric training, on average, elicited an overall increase 76% greater than Control for all musculature (F(1,6) = 6.2–35.5, *P* = 0.001–0.05, β = 0.7–0.9), except for the RRA in which the Control group had a greater response of increasing peak EMG amplitudes (F(1,6) = 6.1, *P* = 0.05, β = 0.7). Dynamic training elicited on average a 77% greater increase in peak EMG amplitude than Control for all musculature except for some gluteal (LGMax, RGMax) and abdominal (REO) muscles (F(1,6) = 6.4–60.2, *P* = 0.001–0.05, β = 0.7–1.0). The Control group had a greater effect on increasing peak EMG amplitudes than Dynamic training for REO muscles (F(1,6) = 7.0, *P* = 0.04, β = 0.8).

Combo trial performance revealed Dynamic training had a 25% overall greater effect on increasing peak EMG amplitudes compared with Isometric training. Dynamic training had a greater effect on some left and right back, abdominal and gluteal (LUES, LEO, LGMax, RUES, REO, RIO, RGMax) musculature (F(1,6) = 8.8–40.4, *P* = 0.03–0.001, β = 0.8–1.0); while Isometric training increased LIO, LGMed, and RLAT EMG amplitudes greater than Dynamic training (F(1,6) = 6.0–9.0, *P* = 0.03–0.05, β = 0.7–0.8). Isometric training increased overall peak EMG amplitudes 84% more than Control, with significant increases in left abdominal (LEO, LIO), left gluteal (LGMax, LGMed), right back (RLAT, RLES), right abdominal (RRA, RIO), and RGMed musculature (F(1,6) = 10.0–35.9, *P* = 0.001–0.02, β = 0.8–1.0); while the Control group had a greater effect on than Isometric training in the RUES musculature (F(1,6) = 6.3, *P* = 0.05, β = 0.7). Dynamic training elicited a similar effect, yielding a 88% greater increase in peak EMG amplitudes than Control, with significant differences in response for some left back (LUES), left abdominal (LRA, LEO), left gluteal (LGMax, LGMed), right back (RUES, RLES), right abdominal (RRA, REO, RIO), and right gluteal (RGMax, RGMed) musculature (F(1,6) = 6.0–39.1, *P* = 0.001–0.05, β = 0.7–1.0); while the Control group did not show any greater effects than Dynamic training.

During Knee trials, Isometric training increased overall peak EMG amplitudes 17% greater than Dynamic training with significant changes in some left back, abdominal, and gluteal (LLES, LEO, LGMax), right back (RLAT, RLES), and right gluteal (RGMAX, RGMed) musculature (F(1,6) = 6.0–13.8, *P* = 0.01–0.05, β = 0.7–0.9); while Dynamic training had a greater effect on LGMed, RUES, and RIO musculature (F(1,6) = 6.0–7.1, *P* = 0.04–0.05, β = 0.7–0.8). Isometric training increased overall EMG amplitudes 99% more than Control with significant differences in left back (LUES, LLES), left gluteal (LGMax, LGMed), right back (RLAT, RUES, RLES), right abdominal (RRA, REO, RIO), and right gluteal (RGMax, RGMed) muscles (F(1,6) = 6.2–26.3, *P* = 0.005–0.05, β = 0.7–1.0). Dynamic training also increased overall EMG amplitudes 99% more than Control with significant changes in the left back (LUES, LLES), LIO, left gluteal (LGMax, LGMed), right back (RUES, RLES), right abdominal (RRA, REO, RIO), and right gluteal (RGMax, RGMed) musculature (F(1,6) = 6.0–39.9, *P* = 0.001–0.05, β = 0.7–1.0). The Control group did not experience any changes in EMG amplitudes that were greater than Isometric or Dynamic training.

Interestingly, an observed pattern of muscular activation and relaxation was recorded in some muscles after Dynamic training during all strike trials. Figure 5 exemplifies the left and right back musculature before and after Dynamic training during a Jab trial. The pretraining EMG pattern shows a typical muscular profile during the strike; while after training, a distinct pattern of activation and relaxation ("double peak") is observed in the UES muscles.

Peak EMG amplitudes before and after Isometric and Dynamic trainings and Control are summarised in Figure 4 with sample muscular activation patterns shown in Figure 5.

Discussion

The results suggest that the Isometric training protocol was superior for enhancing impact force than the Dynamic protocol or Control, while the Dynamic training protocol was superior in enhancing strike velocity compared with Isometric training or Control groups. Interestingly, while Isometric and Dynamic training groups both experienced increases in peak EMG activity, the Dynamic training group was observed to experience changes in the measured motor patterns involving a shift from a typical single peak of activation to peaks of muscular activation and relaxation.

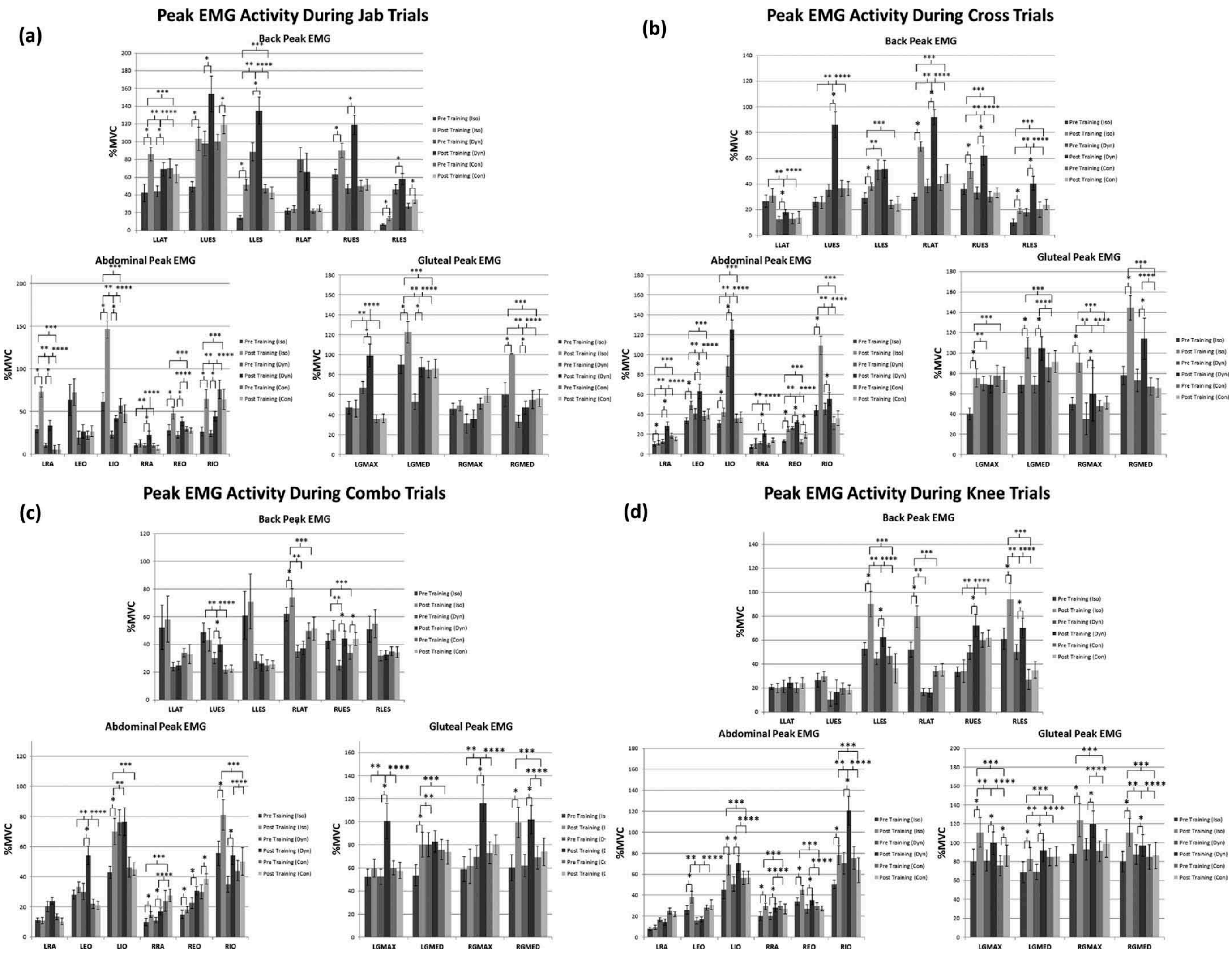

Figure 4. Peak EMG amplitudes during (a) Jab, (b) Cross, (c) Jab–Cross Combination ("Combo"), (d) Knee strikes.
* – statistically significant ($P < 0.05$) difference within training group. ** – statistically significant ($P < 0.05$) difference between Isometric and Dynamic training groups. *** – statistically significant ($P < 0.05$) difference between Isometric and Control training groups. **** – statistically significant ($P < 0.05$) difference between Dynamic and Control training groups.

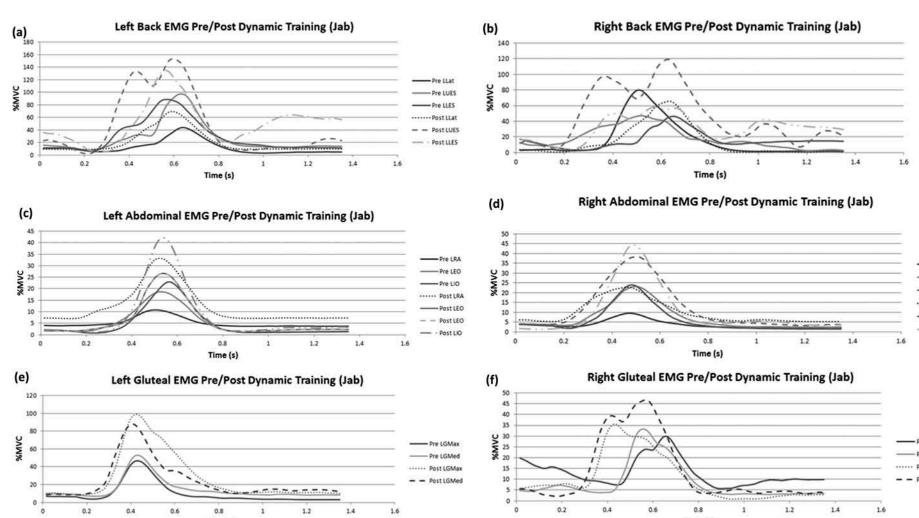

Figure 5. (a) Back (a, b), Abdominal (c, d), and Gluteal (e, f) EMG signals for the Jab strike before and after Dynamic core training. Note the difference in pattern in the UES (LUES, RUES) highlighted in Figure 5(a,b).

The use of EMG to investigate motor control strategies in martial arts striking has grown in recent years (Machado, Osório, Silva, & Magini, 2010; Neto & Magini, 2008; Quinzi, Camomilla, Di Mario, Felici, & Sbriccoli, 2015; Sbriccoli et al., 2010; Sorensen, Zacho, Simonsen, Dyhre-Poulsen, & Klausen, 1996), but investigation of the use of core musculature in martial arts performance is limited to 1 study the authors are aware of (McGill et al., 2010). In processing EMG signals, a low pass filter cut-off frequency of 2.5 Hz was selected to best translate the EMG signal to that of the force generated by the torso musculature (Brereton & McGill, 1998). However, this cut-off was determined in participants who were not highly trained individuals. Evidence exists that trained individuals are able to recruit a greater proportion of motor units as well as a reduced electromechanical delay in muscular activation. It is possible that the participants in this study possessed this characteristic and their faster response with less electromechanical delay would have been better represented with a higher cut-off frequency than an untrained population. However, work by McGill et al. (2010) with elite MMA fighters investigated this issue and found that EMG data processed at 3.5 and 4.5 Hz cut-off frequencies did not affect the pattern of the EMG signal. Given that McGill's population of elite MMA fighters falls further away from the untrained population than club Muay Thai fighters, the use of a 2.5 Hz cut-off frequency for low pass filtering appears justifiable. Other limitations in the interpretation of this study include possible day-to-day differences in EMG amplitude. For example, skin/adipose thickness is known to influence EMG amplitude. Participants did not change body mass more than 1 kg over the trial suggesting this is a remote possibility. Further, the EMG amplitudes were normalised which removes any influence of differences in day-to-day absolute amplitudes. While there is no method to compare Dynamic training and Isometric training to create an equitable workload, we were very conscious of this and tried to create an equitable volume in terms of duration and load challenge. Finally, the numbers of participants were relatively small given the availability of qualified and suitable athletes. However, even with the limited numbers significance in effect was found. This suggests that the effect size is probably larger than was found even with this smaller sample size.

There appears to be a link between enhanced impact force and increases in torso stiffness. Evidence supports the notion that Isometric core training enhances torso stiffness (Lee & McGill, 2015) and effective mass, thus allowing the striker to impart greater impact forces while minimising or "stiffening out" any torso eccentric micro-movements. Stiffer core muscles stabilising the spine appear to prevent "energy leaks" or "giving way" (McGill, 2014 documents several examples). This appears to be a viable candidate mechanism for enhancing impact force. This general notion appears to be corroborated with the increases in peak torso EMG activity, as increased muscular activation and enhanced synchronicity of core/hip muscular activation is linked to enhancements in core stiffness (or what has been termed as a functional "superstiffness", Brown & McGill, 2009b; McGill, 2014). It is postulated that enhanced strike velocity following Dynamic core training is due to changes in muscle activation patterns (Figure 5). Existing evidence links rates of muscular relaxation to creating high-speed athletic movement; literature supports this claim for martial arts striking (McGill et al., 2010), golf driving, and sprinting (McGill, 2014). When comparing the differences between the Isometric and Dynamic protocols, periods of muscular relaxation in the Dynamic exercises appear to be the main difference, particularly during the third block of Dynamic exercises. While little evidence exists on how muscular relaxation can be trained, except for work by Matveyev (1981), the idea of training rates of muscular relaxation to mimic this high force, high velocity motor pattern agrees with the "Principle of Dynamic Correspondence" explained by Verkhoshansky and Verkhoshansky (2011).

Typical of many studies, this investigation sheds new light into the core training methods of Muay Thai practitioners, yet spawns new questions to be answered in the future. Both Isometric and Dynamic trainings enhanced separate properties associated with powerful Muay Thai striking. While Isometric training was superior in enhancing impact force and Dynamic training was superior for enhancing strike velocity, investigation into how the 2 programmes performed together would provide insight on enhancing both aspects. Further, what is the role of increased EMG activity to the enhanced athletic characteristics – does increased EMG signal alone affect impact force and strike speed, or do synchronisation of muscular activation and altered patterns of activation/relaxation play a larger role? Further, as stated above, little informed insight exists in how muscular relaxation can be trained. This study provided some evidence to suggest that Dynamic training can alter motor patterns to create activation–relaxation cycles, but further investigation is needed to understand mechanisms that will underpin eventual application.

Disclosure statement

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