Ballistic Abdominal Exercises: Muscle Activation Patterns During Three Activities Along the Stability/Mobility Continuum

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Abstract

McGill, SM, Karpowicz, A, and Fenwick, CMJ. Ballistic abdominal exercises: muscle activation patterns during three activities along the stability/mobility continuum. *J Strength Cond Res* 23(3): 898–905, 2009—The purpose of this study was to document the muscle activity and spine motion during several tasks requiring rapid abdominal contraction. Eight healthy men from a university population were instrumented to obtain surface electromyography of selected trunk and hip muscles, together with video analysis to calculate joint moments and electromagnetic lumbar spine position sensor to track spine posture. Exercises included a punch, throw, and a ballistic torso-stiffening maneuver. This study found that no muscle turned on significantly before any other muscle during both the 1-in. punch and ballistic torso-stiffening maneuver. Conversely, there was a significant order or muscle onset during the baseball throw. Muscles reached peak activation significantly before any other muscle during the baseball throw and 1-in. punch, but there were no significant differences for the torso-stiffening maneuver. The exercises quantified in this study demonstrated how muscle contraction dynamics change to meet differing demands for stiffening, for force/moment production, and for rapid movements. Specifically, it seems that there is an order of contraction when movement is the goal but not when just spine stability is required. Thus, a different intensity of abdominal bracing is required to achieve the different objectives of sports tasks and exercises.

Key Words clinical technique, corrective exercise, lumbar

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Introduction

Quantifying the joint mechanics and muscle activation patterns of a wide variety of top athletes has revealed an interesting feature. Whereas some are strong, others seem to be extremely proficient at their sport, despite not scoring highly on standard strength tests. However, many have the ability to contract their torso muscles very quickly and, just as quickly, relax them (8). In older Russian literature, the relaxation rates measured in elite sportsmen was 8 times faster than nonathletes (summarized by Mel Siff, but based primarily on Matveyev) (9,5). Consider the elite golfer who develops swing speed with very modest muscle activity. Too much muscle force would cause muscle stiffness, which slows the swing. Then, just before, and during, impact the muscles are contracted, quickly stiffening the torso (8). Thus, developing speed requires ballistic contractions to initiate the motion but then relaxation to preserve the acquired speed. Then, if force is required towards the end of the motion, rapid stiffening is required. However, there is not much data available to provide insight into various mechanisms associated with this rapid stiffening; thus, we were motivated to explore ballistic muscle contraction in the torso and hip muscles. Ultimately, this knowledge could be helpful to optimize training and the enhancement of this ability. The purpose of this study was to document the muscle activation patterns of subjects who began relaxed and then performed the "1-in. punch," a maximal effort baseball throw and maximal voluntary contraction and relaxation of the torso musculature. This study is not designed to investigate the skill involved in throwing a baseball, punching, or stiffening the torso, but rather to compare motor patters between activities with large, small, and no motion of the torso. These exercises were all chosen to challenge the abdominal musculature. However, each exercise varied in the amount of stability versus mobility, and we wanted to test a range along these continuums while satisfying the constraints of a required rapid muscle response. Thus, the ballistic torso contraction had no mobility but high stability (preparing for a punch), whereas delivering a punch had elements of stability with subsequent mobility, and a throw required much more mobility but within the constraints of remaining stable.

There are 2 hypotheses for this study: (a) During the torso-stiffening maneuver, no muscle will turn on or reach peak activation significantly before any other muscle; and (b) when movement of the torso is required, muscle onset times and time to peak activation will be significantly different; otherwise, the torso will be too stiff to move.

Methods

Experimental Approach to the Problem

This basic science investigation was intended to assess muscle onset times, the time to peak muscular activation, along with the peak muscle force produced during the exercises. Also, spine posture was monitored to investigate some of the compromising spine postures that these exercises require.

Subjects

Eight healthy men aged 21.6 years (*SD* 4.1), 1.82 m tall (*SD* 0.06), with a mass of 74.6 kg (*SD* 10.7) participated in this study. All subjects were recreationally active; however, the tasks were novel to some of the participants. Participants were given instructions on how to properly complete the exercises, but the skill level of each participant was not important for this study. We do note that all participants were observed to be good ball throwers. All subject recruitment and data collection procedures were performed in accordance with the University Office of Research and Ethics guidelines. Also, written informed consent was gained in agreement with the MSSE guidelines.

Procedures. Sixteen channels of electromyography (EMG) were collected from electrode pairs placed bilaterally over the following muscles: rectus abdominis lateral to the navel, external oblique approximately 3 cm lateral to the linea semi lunaris but on the same level of rectus abdominis electrodes, internal oblique caudal to the external oblique electrodes and the anterior superior iliac spine and still cranial to the inguinal ligament, latissimus dorsi over the muscle belly when the arm was positioned in the shoulder mid-range, thoracic erector spinae approximately 5 cm lateral to the spinous process (actually longissimus thoracis and iliocostalis at T9), lumbar erector spinae approximately 3 cm lateral to the spinous process (actually longissimus and iliocostalis at L3), right gluteus medius in the muscle belly found by placing the thumb on the anterior superior illiac spine and reaching with the fingertips around to the gluteus medius, gluteus maximus in the middle of the muscle belly approximately 4 cm lateral to the gluteal fold, rectus femoris approximately 5 cm caudal to the inguinal ligament, and biceps femoris over the muscle belly midway between the knee and hip. The skin was shaved and cleansed with a 50/50 H_2O and ethanol solution. Ag-AgCl surface electrode pairs were positioned with an interelectrode distance of approximately 2.5 cm. The EMG signals were amplified and then A/D converted with a 12-bit, 16-channel A/D converter at 2048Hz. Each subject was required to perform a maximal voluntary contraction (MVC) of each measured muscle for normalization of each channel. 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. Participants also performed an isometric reverse curl-up by adopting a supine position where they attempted to lift their pelvis off the table while a research assistant restrained their knees. Subjects were further instructed to attempt to twist right and left. For the spine extensors and gluteal muscles, a resisted maximum extension in the Biering Sorensen position was performed (7). A specific gluteus medius normalizing contraction was also attempted with resisted side lying 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 rectus femoris were attempted with isometric knee extension performed from a seated position with simultaneous hip flexion on the instrumented side. The maximal amplitude observed in any normalizing contraction for a specific muscle was taken as the maximum for that particular muscle. To understand contraction dynamics, the EMG signals were normalized to these maximal contractions after full-wave rectification and low-pass filtering with a second-order Butterworth filter. A cut-off frequency of 2.5 Hz was used to mimic the EMG to force frequency response of the torso muscles (1). To estimate time of peak muscle activation and muscle onset and offset times, the full wave rectified EMG signals were low-pass filtered with a second-order Butterworth filter using a 50-Hz cut-off frequency (4). Muscle onset times and time of peak muscle activations of all muscles were determined relative to the timing of the left internal oblique (LIO) for the baseball throw and ballistic torso-stiffening maneuver and relative to the time of the peak punching force for the 1-in. punch. Muscle offset times were determined as the elapsed time between peak muscle activation and the return to its preactivation state. Further, a comparison of the elapsed time from onset to peak and peak to offset was made.

Lumbar spine position was measured approximately three orthopaedic axes (flexion, lateral bend, and twist) using a 3 Space IsoTRAK electromagnetic tracking instrument (Polhemus Inc, Colchester, Vt). This instrument consists of 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 zero degrees of flexion-extension, lateral bend, and twist). A second transmitter was strapped to the lateral femoral condyle of the right leg to track hip motion.

Figure 1. Illustration of the different exercises completed during this study. (A) 1-in. punch; (B) baseball throw; (C) pre–torso-stiffening maneuver; and (D) ballistic torso-stiffening maneuver.

Description of Exercises

Exercises are shown in Figure 1. Ballistic torso contraction: Standing relaxed, subjects tried to activate their abdominal wall as fast as possible, as if they were going to be "hit in the belly" and then, just as quickly, relax. Three trials were conducted after a practice session.

Baseball throw: Beginning in a relaxed posture, an 11-in. softball (fastball) is thrown overhand into a net.

One-inch Punch: The 1-in. punch, made famous by Bruce Lee, begins with the subject relaxed and the fingertips of the right outstretched arm barely touching a padded force transducer mounted rigidly to the wall at shoulder height. Then, as quickly and as forcefully as possible, the heel of the hand punches the transducer. The emphasis is on abdominal contraction as the prime mover and stiffener.

Statistical Analyses

Peak muscle activation was analysed using a one-way repeated-measures analysis of variance (ANOVA) (Peak muscle activation between factor exercise = 3 levels; $\alpha = 0.05$), whereas muscle timing and time to peak muscle activation were analyzed independently using a one-way ANOVA (muscle onset time and time to peak within factor muscle = 16; $\alpha = 0.05$). Both ANOVA analyses were followed by a least-squares means post hoc analysis, where significant main effect differences were integrated.

Note three trials of each exercise were completed as an accuracy measure to ensure the precision of the means calculated.

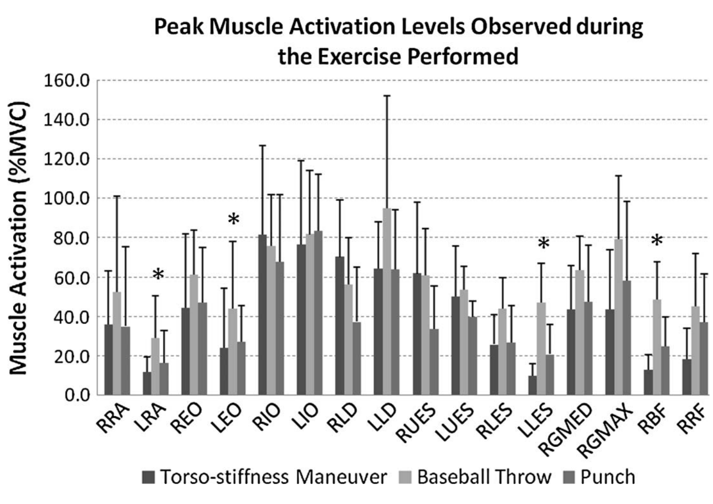

Figure 2. Illustration of the effect that the exercise performed had on each muscle's activation level. Bars represent peak muscle activation levels averaged across all participants. *SD*s are also indicated. Stars represent statistical significance ($p < 0.05$).

Results

Muscle Activation Levels

For the left external oblique (LEO), exercise had a main effect on muscle activation levels (Figure 2). During the baseball throw, the peak muscle activation level of 44.2% MVC was significantly higher than the activation levels of the punch at 27.2% MVC and the torso-stiffening maneuver at 24.1% MVC ($F = 10.60$; $p = 0.0019$).

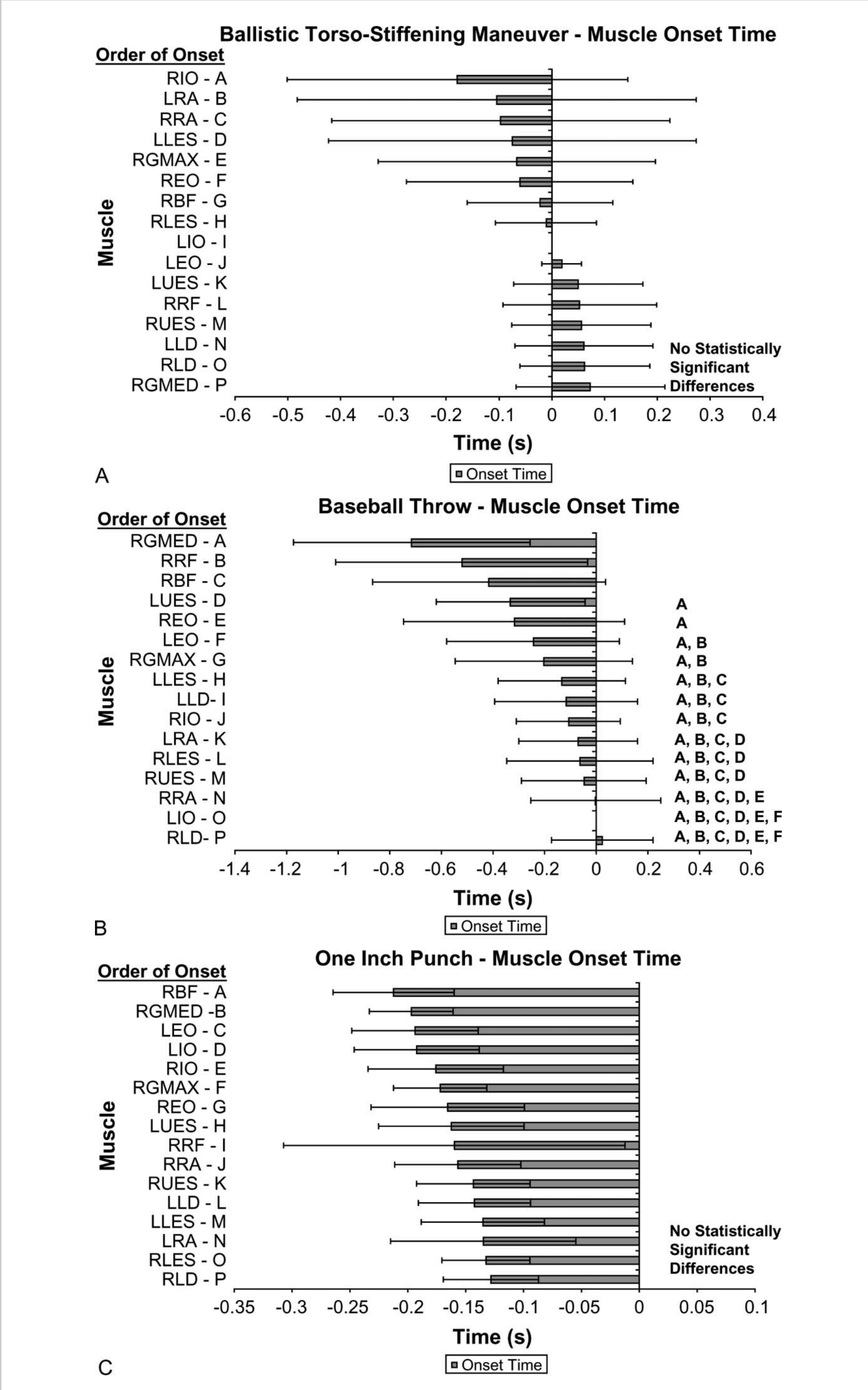

Figure 3. Illustration of the muscle onset order for the (A) punch; (B) baseball throw; and (C) ballistic torso-stiffening maneuver. Muscles were ranked alphabetically with respect to their order of onset (muscle A was the first muscle to turn on). If a muscle turned on significantly before another, the faster muscles corresponding letter was placed on the right hand side of the graph, in line with the muscle that it was faster than.

The left lower erector spinae (LLES) had significantly larger peak activation during the baseball throw (47.0% MVC) than both the punch (20.8% MVC) and the torso-stiffening maneuver (9.9% MVC) ($F = 13.96$; $p = 0.0006$). The left rectus abdominus (LRA) had significantly higher peak activation during the baseball throw at 29.2% MVC than both the punch and the torso-stiffening maneuver at 16.4 and 12.0% MVC, respectively ($F = 6.91$; $p = 0.0090$). During the baseball throw, the observed peak activation of 48.8% MVC from the right bicep femoris (RBF) was significantly higher than the activation levels observed during both the punch at 25.0% MVC and the torso-stiffening maneuver at 12.9% MVC ($F = 16.56$; $p = 0.0003$).

No significant differences were found between exercises and the muscle activation levels produced by the LIO, the left latissimus dorsi (LLD), left upper erector spinae (LUES), right external oblique (REO), right gluteus maximus (RGMAX), right gluteus medius (RGMED), right internal oblique (RIO), right latissimus dorsi (RLD), right lower erector spinae (RLES), right rectus abdominus (RRA), right rectus femoris (RRF), and right upper erector spinae (RUES) muscles.

Muscle Onset Time and Time to Peak Activation

There were significant differences between muscle onsets during the baseball throw only ($F = 5.05$; $p < .0001$). For example, RGMED turned on almost 400 ms faster than the LUES and almost 740 ms faster than the RLD. For the punch ($F = 1.75$; $p = 0.0545$) and the ballistic torso-stiffening maneuver ($F = 0.87$; $p = 0.5997$), no muscle turned on significantly before any others (see Figure 3 for significant order of muscle onset times). Notice that there was not a typical ordering of onset between tasks. For example during the throw and punch exercises, the gluteus

TABLE 1. Comparison of elapsed time for each muscle from peak activation back to the preactivation level (offset time) during the torso-stiffening maneuver, baseball throw, and punch.

		Muscle Timing (s)															
		RRA	LRA	REO	LEO	RIO	LIO	RLD	LLD	RUES	LUES	RLES	LLES	RGMED	RGMAX	RBF	RRF
TSM	X	0.268	0.266	0.317	0.362	0.259	0.373	0.307	0.295	0.357	0.283	0.326	0.524	0.469	0.331	0.292	0.692
	SD	0.170	0.216	0.145	0.156	0.151	0.202	0.158	0.127	0.189	0.216	0.157	0.376	0.181	0.191	0.185	0.780
BBT	X	0.255	0.244	0.562	0.449	0.248	0.766	0.481	0.703	0.916	1.219	1.166	1.112	1.024	0.481	0.955	1.054
	SD	0.099	0.133	0.411	0.198	0.218	0.602	0.384	0.283	0.666	0.590	0.458	0.641	1.049	0.292	0.683	0.740
P	X	0.141	0.144	0.204	0.244	0.287	0.441	0.205	0.272	0.176	0.346	0.400	0.220	0.509	0.184	0.268	0.288
	SD	0.091	0.094	0.078	0.095	0.359	0.436	0.047	0.198	0.071	0.253	0.536	0.098	0.329	0.136	0.223	0.217

RRA = right rectus abdominus; LRA = left rectus abdominus; REO = right external oblique; LEO = left external oblique; RIO = right internal oblique; LIO = left internal oblique; RLD = right latissimus dorsi; LLD = left latissimus dorsi; RUES = right upper erector spinae; LUES = left upper erector spinae; RLES = right lower erector spinae; LLES = left lower erector spinae; RGMED = right gluteus medius; RGMAX = right gluteus maximus; RBF = right bicep femoris; RRF = right rectus femoris.

TABLE 2. The ratio of the elapsed time from peak activation to muscle offset over the elapsed time from muscle onset to peak activation.

		Muscle timing (s)															
		RRA	LRA	REO	LEO	RIO	LIO	RLD	LLD	RUES	LUES	RLES	LLES	RGMED	RGMAX	RBF	RRF
TSM	X	1.857	2.072	1.751	2.265	1.156	2.087	2.678	2.518	2.996	1.444	2.550	3.455	3.231	2.642	2.727	3.886
BBT	X	0.973	0.958	1.426	0.757	0.716	1.914	1.210	2.775	2.168	1.685	3.830	2.191	1.312	1.432	1.591	1.158
P	X	1.034	0.897	1.374	1.651	1.711	2.986	1.330	2.308	0.989	2.253	1.934	2.192	2.366	2.105	2.713	2.405

RRA = right rectus abdominus; LRA = left rectus abdominus; REO = right external oblique; LEO = left external oblique; RIO = right internal oblique; LIO = left internal oblique; RLD = right latissimus dorsi; LLD = left latissimus dorsi; RUES = right upper erector spinae; LUES = left upper erector spinae; RLES = right lower erector spinae; LLES = left lower erector spinae; RGMED = right gluteus medius; RGMAX = right gluteus maximus; RBF = right bicep femoris; RRF = right rectus femoris.

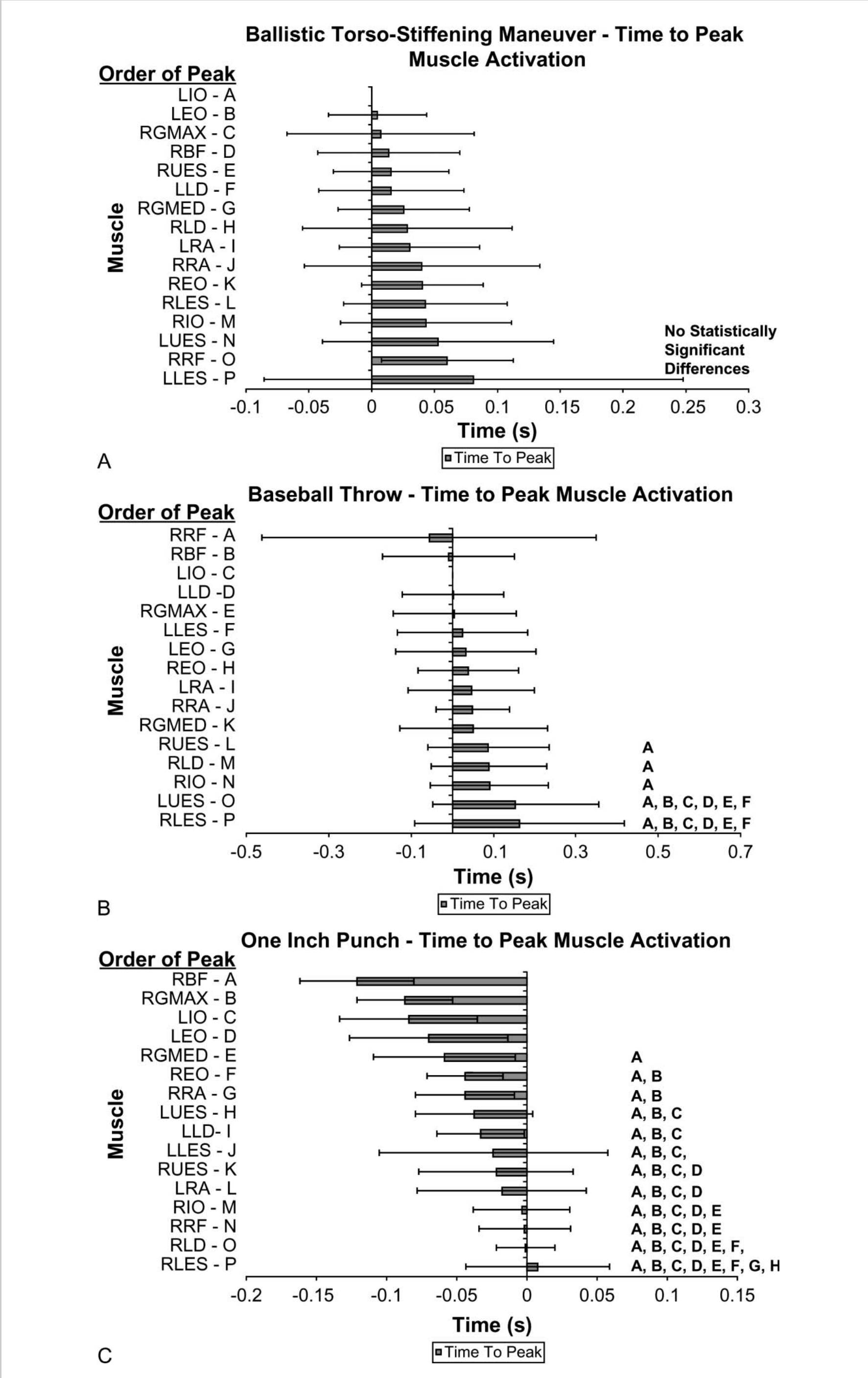

Figure 4. Illustration of the timing of peak muscle activation order for the (A) punch; (B) baseball throw; (C) ballistic torso-stiffening maneuver. Muscles were ranked alphabetically with respect to the timing of their peak activation (muscle A was the first muscle to reach its peak activation). If a muscle peaked significantly before another, the faster muscles corresponding letter was placed on the right hand side of the graph, in line with the muscle that it was quicker at reaching peak activation than.

medius was very early, whereas it was the last to turn on in the ballistic torso-stiffening maneuver. Peak muscle forces showed a different pattern. When performing the baseball throw ($F = 1.81$; $p < 0.0456$) and the punch ($F = 5.48$; $p = <.0001$), both exercises had muscles reaching peak activation significantly before other muscles, whereas no muscle consistently reached peak activation significantly before any other muscle during the ballistic torso-stiffening maneuver ($F = 0.75$; $p = 0.7290$). During the baseball throw, the RRF reached peak activation a little more than 140 ms before the RUES and was almost 220 ms before the RLES. The right bicep femoris (RBF) was more than 160 and 170 ms faster at reaching its peak activation than the left upper erector spinae and RLES, respectively. During the 1-in. punch, the RBF muscle was 62 ms faster at reaching peak activation than the RGMED muscle and almost 130 ms faster than the RLES muscle. Also, the RGMAX was close to 43 ms faster than the REO and 95 ms faster than the RLES. See Figure 4 for a list of the order that muscles peaked and the statistically significant differences. Once again, the stiffening task caused different responses than the throwing and punching exercises did. Here the biceps femoris peaked very early in the throw and punch but very late in the torso-stiffening maneuver. There was asymmetry between right and left muscle peaks in all tasks.

Muscle Offset Times

During the torso-stiffening maneuver, baseball throw, and punch, the average offset times for the RRA muscle were 0.268 seconds (*SD* 0.170), 0.225 seconds (*SD* 0.099), and 0.141 seconds (*SD* 0.091), respectively. Typically, the rectus abdominis displayed the most rapid relaxation rate. Offset times for all muscles during the tasks performed are shown in Table 1. Note that the left side of each muscle pair was quite

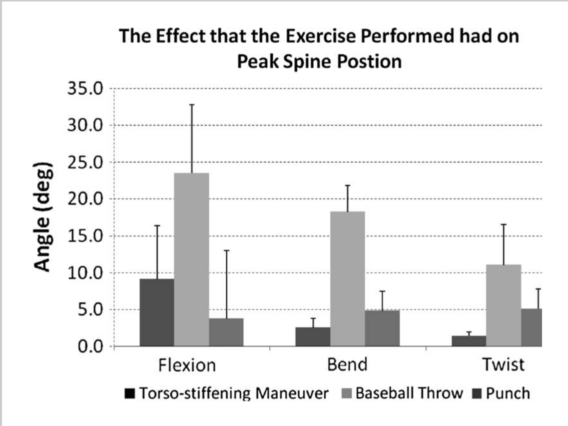

Figure 5. Illustration demonstrating how the exercise performed affected the peak spine angle. The baseball throw had significantly more flexion, lateral bend, and twist motion than did both the punch and torso-stiffening maneuver. Bars represent peak spine angles averaged across all participants. *SD*s are also indicated.

symmetric during the torso-stiffening maneuver and punch. The only asymmetry seen during the punch was between the RIO and LIO. During the baseball throw, the abdominals displayed the most rapid relaxation rate (i.e., RRA = 0.255 seconds), whereas the back muscles had the least rapid relaxation rate (i.e., LUES = 1.219 seconds).

Ratio of Elapsed Time Between Peak Activation to Muscle Offset More Than the Elapsed Time Between Muscle Onset to Peak Activation

When the torso-stiffening maneuver, baseball throw, and punch exercises were performed, the ratio of offset times over the onset times for the RRA were 1.856, 0.973, and 1.033. See Table 2 for a complete list of ratios for all muscles during the exercises performed. During the baseball throw, the abdominals returned to a state of preactivation roughly as fast as they reached peak activation; however, the back muscles displayed a much longer relaxation rate. The RLES muscles ratio of peak activation to offset compared with peak to onset was 3.830:1.

Spine Position

During the baseball throw, the spine was significantly more flexed at 23.5 degrees than during the punch and torso-stiffening maneuver at 3.7 degrees and 9.1 degrees of flexion, respectively ($F = 13.04$; $p = 0.0008$) (Figure 5).

There was significantly more lateral bend and twist (absolute values) during the baseball throw at 18.2 degrees and 11.0 degrees (bend and twist) than both the punch at 4.8 degrees and 5.1 degrees and the torso-stiffening maneuver at 2.5 degrees and 1.4 degrees (bend: $F = 61.47$; $p \leq 0001$) (twist: $F = 12.29$; $p = 0.0010$).

Discussion

In this study of 3 tasks that represented a continuum of mobility and stability, several phenomena were observed. First, the order of muscle onset does not equal the order of peak activation, nor is muscle offset closely linked to muscle onset. In the tasks that required the most stability and the least mobility, the muscle relaxation rates were the shortest. This may turn out to be a good training exercise for enhancing relaxation rates. In throwing, a task requiring mobility within stability constraints, the relaxation rates were longest, suggesting that the task would not be optimal for training relaxation rates. Thus, muscle onset and offset times seem to be related to both mobility and stability constraints. There are further constraints, for example, most torso muscles create moments about the three orthopedic axes of the spine (6). If a muscle is activated to a higher level, larger moments would occur and would have to be balanced by other muscles. Therefore, force and timing constraints must be placed on the activation level of any given muscle. Also, the spine must first achieve sufficient stability to handle any imposed loads without risk of buckling (3). Stability is achieved only with a balancing of stiff muscles around the spine (2). Changing the activity of a single muscle would require adjustments in

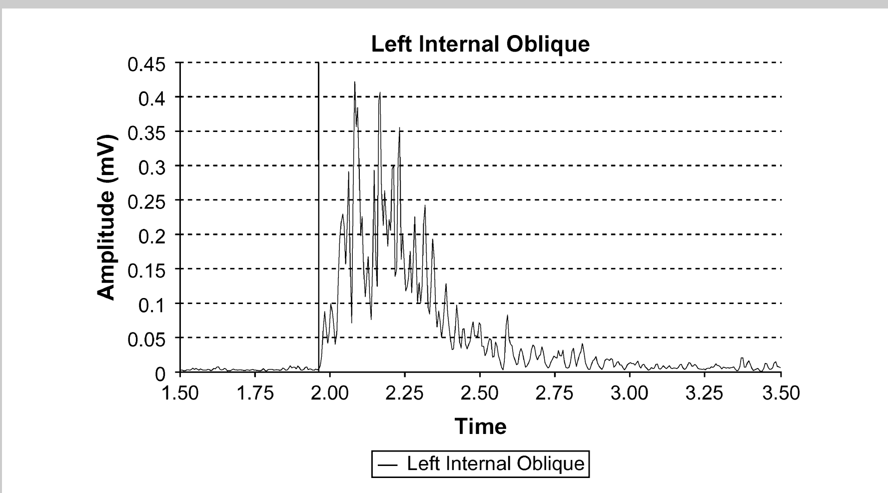

Figure 6. Illustration demonstrating how the onset time was determined. Raw electromyography signals were full-wave rectified and then low-pass filtered at 50 Hz. The researcher inspected the graph and determined when the muscle actually turned on (indicated by the vertical line).

all other muscles to ensure the balance of stiffness. Therefore, as shown by the ballistic torso-stiffening maneuver, when a person quickly stiffens their torso musculature, no muscle turns on or reaches its peak muscle force before another. This muscle activation pattern ensures a balance in the moments produced around the 3 orthopedic axes.

However, when motion of the spine is created during a baseball throw, muscles turn on significantly before other muscles to create continuity of force/moment through the body segment linkage, which includes a twisting moment that produces a twisting motion. Specifically, the task requires the generation of energy from ground forces, which is directed up the legs and transmitted through a stable core (reducing energy leaks). Muscles must be stiff enough to ensure joint stability but not too stiff to impede movement, in turn, making for a slower/weaker throw.

Several limitations influence the interpretation of the results reported here. These were healthy subjects who were not elite athletes or experts in the exercises tested, such that an elite athlete, the elderly, children, and painful patients may respond differently. Also, muscle onset timing was visually determined; however, this inspection was performed by one researcher only, effectively eliminating inter-researcher variability (see Figure 6).

In conclusion, the exercises quantified in this study demonstrated how muscle contraction dynamics change to meet differing demands for stiffening and for force/moment/movement production. Further, while energy is being transferred through the kinetic linkages, the motor control system is able to organize the activity in all muscles to achieve joint stability and balance 3 moments about each joint. Whereas we do not know what is optimal from the data in this study, we do know that different demands for stiffness, stability, and force and moment production cause different patterns of contraction. These data will be informative for those designing exercise programs where ballistic exercise may be chosen to reach specific objectives.

Practical Applications

Different intensities of abdominal bracing are required for different sports and exercises. For example, when spine motion is required, as in the baseball throw, too much abdominal bracing will make the torso too stiff and will slow the explosiveness of the trunk, effectively slowing the velocity of the thrown ball. However, not enough abdominal bracing, or none at all, could lead to unstable movements and a "sloppy" performance, which could increase the risk of injury. However, if little spine motion is required, such as during the torso-stiffening maneuver and the short range punch, a slight increase in the abdominal brace could increase the efficiency of the energy traveling from the ground up through the legs and torso. With little energy lost through the stiff torso, a harder more powerful punch can develop. Thus, muscle relaxation rates are also important performance stability/mobility performance variables. The rapid torso-stiffening maneuver may have the potential to train the rate of muscle contraction and relaxation.

Acknowledgments

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