Quantifying Muscle Patterns and Spine Load during Various Forms of the Push-Up

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ABSTRACT

FREEMAN, S., A. KARPOWICZ, J. GRAY, and S. MCGILL. Quantifying Muscle Patterns and Spine Load during Various Forms of the Push-Up. *Med. Sci. Sports Exerc.*, Vol. 38, No. 3, pp. 570–577, 2006. **Purpose:** This study was conducted to quantify the normalized amplitudes of the abdominal wall and back extensor musculature during a variety of push-up styles. We also sought to quantify their impact on spinal loading by calculating spinal compression and torque generation in the L4–5 area. **Methods:** Ten university-age participants, nine males and one female, in good to excellent condition, volunteered to participate in this study. All participants were requested to perform a maximum of 12 different push-up exercises, three trials per exercise. Surface electromyographic data (EMG) were collected bilaterally on rectus abdominis, external oblique, internal oblique, latissimus dorsi, and erector spinae muscles, and unilaterally (right side) on pectoralis major, triceps brachii, biceps brachii, and anterior deltoid muscles. Spine kinetics were obtained using an anatomically detailed model of the torso/spine. **Results:** This study revealed that more dynamic push-ups (i.e., ballistic, with hand movement) required more muscle activation and higher spine load, whereas placing labile balls under the hands only resulted in modest increases in spine load. Right rectus abdominis (RA) activation was significantly higher than left RA activation during the left hand forward push-up and vice versa for the right hand forward push-up ($P < 0.001$). External oblique (EO) demonstrated the same switch in dominance during staggered hand push-ups ($P < 0.01$). The one-arm push-up resulted in the highest spine compression. Skilled participants showed greater synchronicity with peak muscle activation (plyometric type of contractions) during ballistic push-ups. **Conclusion:** These data will help guide exercise selection for individuals with differing training objectives and injury history. **Key Words:** STRENGTH, TRAINING, SPINE COMPRESSION, PLYOMETRIC, EXERCISE

The muscles of the torso generate force to create three-dimensional moments and contribute stiffness to stabilize the spine (2,3). Some forms of spine stabilization exercise engage the abdominal hoop composed of rectus abdominis, the internal and external oblique, and transverse abdominis muscles in an isometric contraction (9). "Push-up" exercises are sometimes used as a torso training exercise. Clinical observation confirms that performing push-ups elicits back pain in some patients, yet others find them relieving, suggesting that an understanding of the mechanisms will lead to better prevention and rehabilitation technique (9). The objective of the present study was to investigate the mechanisms associated with push-ups by quantifying muscle activation patterns and calculating the resultant spine load for a variety of push-up styles.

Previous studies on push-ups as a therapeutic exercise have focused primarilyon the mechanics of the upper extremity (6,7). Mori (10) measured trunk musculature activation over a variety of exercises, one of which was performing push-ups on a gym ball. Spine load, however, was not calculated. Juker et al. (5) examined the activation profiles of the abdominal musculature during a standard push-up. Surface electrodes were placed over the torso musculature and back extensors, while internal oblique, external oblique, transverse abdominis, and psoas muscles were monitored using intramuscular electrodes. From this study, the flexor moment about L4–5 was calculated to be between 60 and 66 nm. Spine compression was not reported.

Various push-up styles have been used as a training exercise to challenge sagittal mechanics of the torso together with introducing asymmetric hand placement and labile support surfaces intended to challenge torso control-about the frontal and transverse planes (9). The purpose of this study was to qualify the normalized amplitudes of the abdominal wall and back extensor musculature during a variety of push-up styles and quantify their impact on spinal loading. We also sought to calculate spinal compression and torque generation about L4–5. It was hypothesized that both muscle activity and spine load would increase relative to a standard push-up when a labile surface or a change in the rate of contraction is introduced. In addition, the muscle activity of the chest (pectoralis major) and arms (triceps brachii and biceps brachii) was monitored for comparative purposes.

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METHOD

Participants. Ten participants, nine males and one female (age 22–34 yr, mean = 24), volunteered to participate in this study. Participants were in excellent health and reported no history of musculoskeletal or cardiac conditions before this experiment. One participant was a professional football player and another was an elite Olympic-level sprinter; these two were considered excellent athletes given their high performance in sport, and the remainder were fit graduate students. All participants signed consent and information forms approved by the ethics committee on human research at the university.

Tasks. All participants were requested to perform a maximum of 12 different push-up exercises, three trials per exercise. Participants were familiarized with each exercise before the performance of each task. With the exception of performing the standard push-up first, the order of exercises was randomly assigned to each participant. Where possible, push-ups were performed to a metronome to standardize speed of movement, which is related to the speed of change in length of the muscle tendon unit. For instance, each push-up exercise was divided into three components: lowering the body, holding the lowest position, and raising the body. Each component was performed to a count of three, having a total time of 1.5 s per push-up. Exceptions to this timing procedure included the fast eccentric, slow concentric, clapping, and alternating medicine ball push-ups.

The first exercise performed was a standard push-up, intended to provide a comparable baseline for each paticipant (Fig. 1). The participant began with their hands and toes on the floor, shoulder width apart. A neutral spine curvature and straight body position from the shoulder to ankle joint was assumed. With their arms straight,

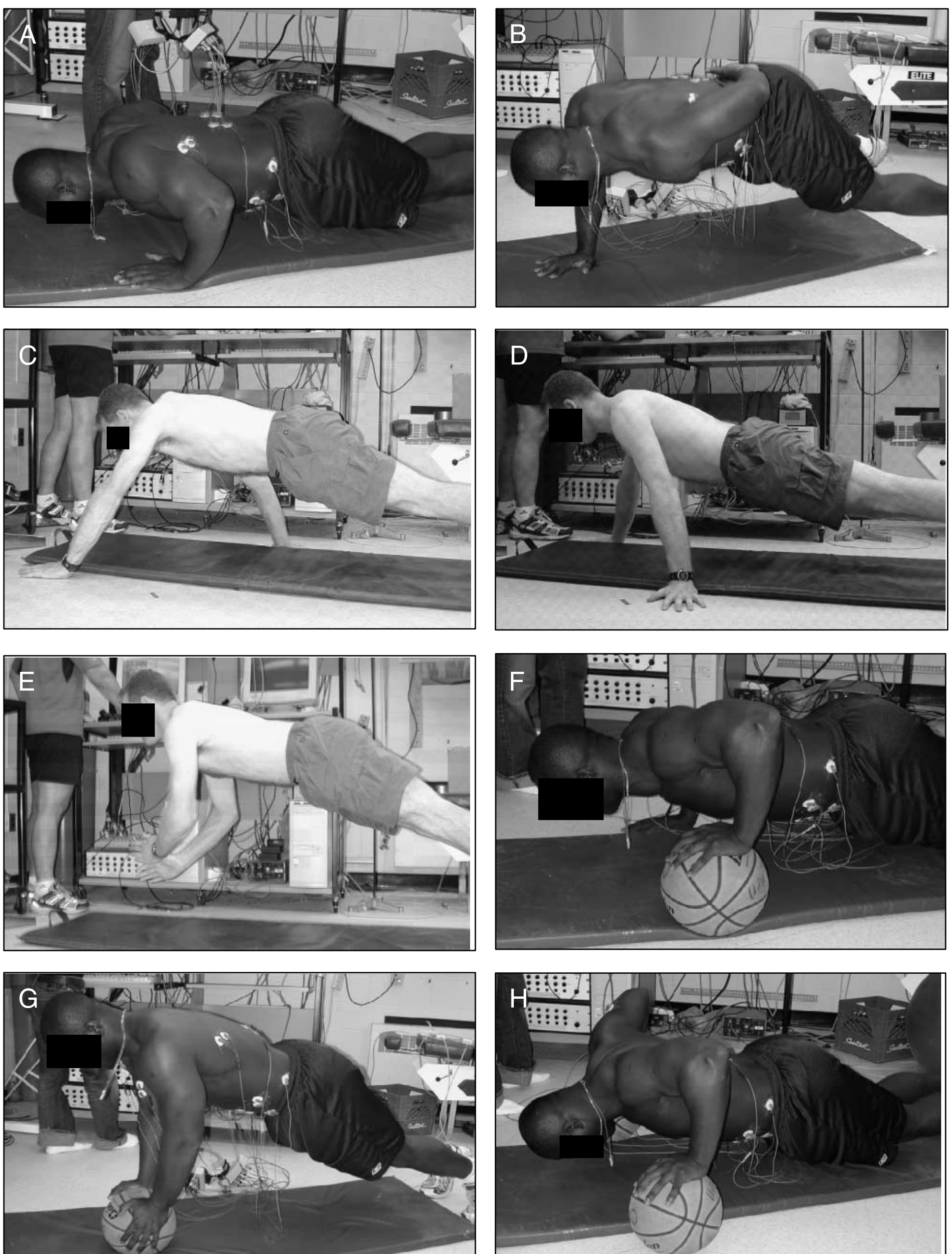

FIGURE 1— (A–H): The various forms of the push-up studied ranged from a standard push-up (A), a single arm (B), uneven hand placement: left forward (C), uneven hand placement: right forward (D), clapping (E), one hand on ball (F), both hands on ball (G), and two hands on two balls (H).

participants were instructed to position the shoulder joint directly above the wrist. On beginning the exercise, the body was lowered toward the floor by bending the arms to 90° at the elbows, after which the body was raised to the initial start position by straightening the arms. The standard push-up was performed at three differing speeds of contraction, with focus on various phases of the push-up. One exercise was performed at a standard pace (as described below), whereas the second and third focused on the fast concentric and slow eccentric phases, respectively. The performance of all subsequent push-ups adhered to similar guidelines to the standard push-up with the following notable exceptions for each push-up type. The single-arm push-up involved placing only one hand on the floor (the right in all cases) while the other arm was placed on the ipsilateral side of the lower back (Fig.1). Push-ups performed using an uneven hand placement required one hand to be placed on the floor 3 inches in front of the shoulder joint and the other hand 3 inches behind the shoulder joint. Push-ups were performed with each hand in either position. Beginning in the standard push-up position, the participants performed clapping push-ups. Participants were allowed to lower their body toward the floor, as in the standard, but were required to extend their elbows rapidly in order to elevate their entire body off the floor and perform a "clap" while elevated. Participants performed push-ups with one hand on a ball (standard basketball); trials were performed with each hand in either position. Alternating ball push-ups involved a similar starting position to that of the one hand on ball style and, similar to the clapping push-up, a rapid elbow extension was required to elevate the entire body from its support surface. Here, the body travels over the ball while elevated and the participant lands with the contralateral hand on the ball. For the push-ups performed with both hands on a single ball, the hands were placed 6 inches apart. Performing push-ups with the hands placed on separate balls allowed for the balls and hands to be placed shoulder width apart.

Data collection. Myoelectric signals were detected with 14 pairs of surface electrodes (AgAgCl) applied to prepared skin over the following muscles on both right and left sides of the body: rectus abdominis (3 cm lateral to the umbilicus); external oblique (~15 cm lateral to the umbilicus); internal oblique (1 cm medial to the anterior superior iliac spine, ASIS); latissimus dorsi (lateral to T9 spinous process over the muscle belly); lumbar erector spinae (3 cm lateral to L3 spinous process). In addition, other muscles were monitored just on the right side of the body: pectoralis major (on an angle midway between the anterior aspect of the humeral head and the nipple over the muscle belly); biceps brachii long head (midway between the anterior aspect of the humeral head and the elbow joint); triceps brachii lateral head (angled medial and inferior over the muscle belly); anterior deltoid (between the lateral border of the clavicle and the deltoid tuberosity on the humerus over the muscle belly). In all cases, specifications followed ISEK standards. The inter-electrode distance was 3 cm, and a common mode rejection ratio (CMRR) for the amplifiers was 80 dB at 60 Hz. A sampling rate of 1024 Hz and a 12-bit A/D converter were used. To optimize accuracy of targeted myoelectric signals through out the experimental tasks, each participant was asked to assume a push-up posture during application of the electrodes to the upper extremity.

Participants performed standardized maximal isometric efforts (MVC) tonormalize (and calibrate) myoelectric signals before the push-up tests. There were 30–90 s of rest time between trials to avoid the effects of fatigue, and the MVC trials were randomized within the MVC testing procedure.

Strategies used for the trunk muscle normalization were chosen from previous studies (8). Briefly, to normalize abdominal musculature, the participant adopted a bent knee sit-up posture with the feet restrained by a strap, the arms crossed over the chest and the trunk forming an angle with the horizontal of approximately 30°. An assistant provided a matching resistance to the shoulders and torso during maximal sit-up, lateral bend, and twist efforts. To normalize the trunk extensors and latissimus dorsi, participants lay prone with torso leaning out over the edge of a test bench with legs restrained and the angle of the torso parallel to the horizontal. With arms crossed over the chest, participants performed an isometric extension exertion against a matched resistance to the shoulders by a research assistant; participants were instructed to retract the shoulders in attempt to squeeze the scapulae together. Normalization of the pectoralis major muscle consisted of the participant lying supine on a test bench with the right shoulder close to the edge of the bench. With the shoulder in a flexed and abducted position, the participant performed an isometric horizontal shoulder adduction toward the midline of the body against a matched resistance provided to the forearm by a research assistant. The strategy used to normalize the anterior deltoid muscle involved the participant adopting a standing posture with the shoulder flexed, arm parallel to the horizontal, and the elbow flexed to 90°. The participant performed an isometric shoulder flexion exertion against a matched downward resistance to the upper arm as applied by an assistant. Finally, normalization of the arm muscles was performed using cables to provide an immovable resistance. The strategy used for the biceps consisted of the participant standing facing a pulley system, with the elbow flexed to almost 90°, holding the handle of the cable attached toward the floor with the forearm supinated. An isometric elbow flexion was performed against the stationary cable. To normalize for the triceps, the participant adopted a standing posture similar to the biceps strategy. Here, the elbow was flexed slightly past 90° and the forearm pronated while holding the handle of the cable attached toward the ceiling and the isometric exertion performed. Each isometric contraction was held briefly (<3 s) to obtain a maximal voluntary isometric contraction for each effort.

TABLE 1. Push-ups ranked by magnitude of muscle activation per muscle.

Muscle	Right Rectus Abdominis		Muscle	Left Rectus Abdominis	
Push-up	% MVC	SD	Push-up	% MVC	SD
No legs	8.6		No legs	14.9	
Standard	24.9	11.3	Standard	20.1	8.3
R forward	30.2	14.9	L forward	23.3	8.2
L on ball	37.4	18.3	Slow eccentric	26.1	12.3
Slow eccentric	37.4	25.5	R forward	29.1	10.7
L forward	39.5	16.0	L on ball	30.8	16.0
R on ball	41.6	24.2	R on ball	32.7	14.7
Two arms on one ball	45.7	34.4	Fast concentric	36.7	16.9
One arm	52.4	18.4	Two on one ball	40.5	28.2
Fast concentric	54.1	28.3	Clapping	41.0	16.8
Clapping	56.7	26.8	One arm	42.8	23.2
Two arms on two balls	61.3	31.3	Two on two balls	50.0	21.3
Alternating	80.2	25.7	Alternating	60.2	23.8
Muscle	**Right External Oblique**		**Muscle**	**Left External Oblique**	
Push-up	**% MVC**	**SD**	**Push-up**	**% MVC**	**SD**
R forward	20.3	8.1	L forward	19.4	13.6
Standard	22.5	11.1	L on ball	23.5	11.9
R on ball	23.4	14.7	Standard	24.7	12.5
Slow eccentric	26.3	13.2	Slow eccentric	27.3	18.9
Two on one ball	32.0	17.9	R on ball	28.7	13.5
L forward	32.2	17.1	Two on two balls	30.0	15.3
Two on two balls	34.2	16.5	R forward	33.4	16.8
L on ball	35.1	15.5	Two on one ball	34.5	18.6
Fast concentric	44.9	17.6	No legs	49.9	
No legs	49.6		Fast concentric	50.6	22.8
One arm	51.3	13.4	One arm	53.6	32.6
Clapping	55.8	30.0	Clapping	63.0	39.6
Alternating	65.8	28.8	Alternating	73.8	36.0
Muscle	**Right Internal Oblique**		**Muscle**	**Left Internal Oblique**	
Push-up	**% MVC**	**SD**	**Push-up**	**% MVC**	**SD**
R forward	21.1	14.1	Standard	26.6	15.7
Standard	21.6	12.5	Slow eccentric	28.2	16.8
Slow eccentric	28.2	21.2	L forward	32.2	19.9
L forward	28.9	22.4	L on ball	33.2	23.4
L on ball	29.3	22.8	R forward	33.8	23.3
R on ball	32.3	26.6	No legs	36.5	
Two on one ball	33.6	36.2	Two on one ball	39.7	32.2
No legs	35.1	0.0	R on ball	40.2	33.9
Two on two balls	45.2	33.2	Two on two balls	48.8	45.2
One arm	46.8	23.1	Fast concentric	64.1	34.6
Fast concentric	54.1	28.3	Clapping	66.6	28.5
Clapping	56.4	42.5	One arm	89.8	52.0
Alternating	74.9	39.7	Alternating	98.9	54.0
Muscle	**Right Latissimus Dorsi**		**Muscle**	**Left Latissimus Dorsi**	
Push-up	**% MVC**	**SD**	**Push-up**	**% MVC**	**SD**
R on ball	9.7	5.6	No legs	0.0	
Standard	10.6	7.3	Two on two balls	11.5	6.8
L on ball	14.5	9.6	L on ball	12.5	8.8
Two on two balls	15.0	13.1	Standard	14.1	9.5
L forward	16.2	9.2	L forward	14.5	11.7
Slow eccentric	16.3	14.0	Slow eccentric	15.3	10.9
Two on one ball	17.3	12.7	Two on one ball	16.7	15.5
Fast concentric	18.6	8.9	R forward	18.2	10.0
One arm	20.7	13.1	R on ball	18.3	15.3
R forward	24.1	21.7	Fast concentric	20.6	11.7
Clapping	27.1	14.0	Alternating	31.5	20.4
Alternating	27.1	20.7	Clapping	44.4	34.9
No legs	34.1		One arm	85.7	41.8
Muscle	**Right Erector Spinae**		**Muscle**	**Left Erector Spinae**	
Push-up	**% MVC**	**SD**	**Push-up**	**% MVC**	**SD**
No legs	4.4		L forward	2.4	1.4
Standard	4.6	4.6	L on ball	2.5	1.0
Two on two balls	4.7	3.4	Two on two balls	2.6	1.0
R on ball	4.8	4.5	Standard	2.7	1.0
L on ball	5.4	6.5	Slow eccentric	2.7	1.2
Slow eccentric	5.5	6.4	R on ball	3.0	1.7
R forward	6.4	7.3	Two on one ball	4.4	2.3
Two on one ball	6.7	6.8	No legs	5.0	
L forward	8.0	11.1	Fast concentric	6.0	3.6
One arm	8.3	5.6	R forward	6.3	8.6
Clapping	9.4	6.5	Clapping	10.8	8.0
Fast concentric	11.7	8.5	Alternating	12.9	5.6
Alternating	20.5	29.3	One arm	28.8	29.9
Muscle	**Right Pectoralis Major**		**Muscle**	**Right Anterior Deltoid**	
Push-up	**% MVC**	**SD**	**Push-up**	**% MVC**	**SD**
L on ball	49.2	32.2	R on ball	35.6	14.9
No legs	49.6		Slow eccentric	39.7	17.6

TABLE 1. (*continued*)

Muscle	Right Pectoralis Major		Muscle	Right Anterior Deltoid	
Push-up	% MVC	SD	Push-up	% MVC	SD
Slow eccentric	56.8	38.1	Standard	42.0	14.0
R forward	57.0	32.6	Two on two balls	43.7	17.4
L forward	57.7	44.9	R forward	45.0	19.6
Standard	61.2	38.3	L on ball	48.0	19.2
R on ball	61.4	51.5	Two on one ball	50.6	21.9
Two on one ball	68.7	39.9	L forward	52.6	22.1
One arm	81.2	54.3	Fast concentric	52.6	19.6
Two on two balls	81.4	54.1	Alternating	56.1	31.4
Fast concentric	87.4	55.0	No legs	56.2	
Alternating	88.0	61.2	Clapping	60.8	19.8
Clapping	88.9	49.2	One arm	69.8	20.8
Muscle	**Right Triceps Brachii**		**Muscle**	**Right Bicep Brachii**	
Push-up	**% MVC**	**SD**	**Push-up**	**% MVC**	**SD**
No legs	41.4		Standard	4.4	2.3
R on ball	51.8	28.3	One arm	5.5	2.1
L forward	52.7	21.9	R forward	5.6	2.7
Slow eccentric	55.0	31.7	Two on one ball	7.0	2.9
Two on two balls	66.0	25.4	R on ball	7.1	2.5
Standard	66.0	17.6	Slow eccentric	7.2	4.5
R forward	66.0	15.4	Fast concentric	7.2	2.4
Fast concentric	67.6	28.3	Two on two balls	8.1	3.4
Two on one ball	68.9	16.2	L on ball	8.1	10.6
L on ball	69.2	27.6	L forward	8.6	5.2
One arm	78.7	18.1	No legs	25.7	
Alternating	84.1	34.2	Alternating	27.4	19.8
Clapping	88.6	21.2	Clapping	30.6	16.9

Data processing. Following data collection, all myoelectric signals were A/D converted (12-bit resolution), filtered to create a linear envelope of each EMG signal, and normalized to each participant's MVC. A single-pass, low-pass Butterworth filter was used, and a cutoff frequency of 2.5 Hz was chosen to approximate the transfer function of torso muscle to create force from their respective neural drive (1). Trials ranged from 6 to 8 s in duration. The duration of push-up styles such as the fast concentric, slow eccentric, clapping, and alternating ball trials varied slightly across participants. Following data processing, SAS v9.1 was used to run paired *t*-tests comparing hand position with peak muscle activation (%MVC) using a Bonferroni correction for multiple T.

Calculation of the total lumbar spine moment and compression. Spine kinetics were obtained using the anatomically detailed model of Cholewicki and McGill (2). Cross-sectional area of the following muscles on each side of the body affecting L4–5 were as follows: rectus abdominis 10 cm^2, external oblique 19 cm^2, internal oblique 8 cm^2, latissimus dorsi 16 cm^2, thoracic longissimus thoracis and iliocostalis lumborum 14 cm^2, all lumbar longissimus and iliocostalis 52 cm^2, quadratus lumborum 5 cm^2, and multifidus 5 cm^2. Stress values were adjusted so that the total moment required to perform the standard push-up matched the moment measured by a linked model representation of a participant performing the task. The normalized EMG amplitudes (% MVC) were multiplied by the cross-sectional area (cm^2) and stress ($N \cdot cm^{-2}$) to predict the muscle force (N). Each muscle force was applied to the skeleton, and the total amount of compression at L4–5 was computed. Once the stress coefficients were established for the standard push-up, they were applied to all other styles of push-up to facilitate analysis of the dynamic push-ups, which included "moving hands" and a ballistic exercise such as the hand-clapping push-up.

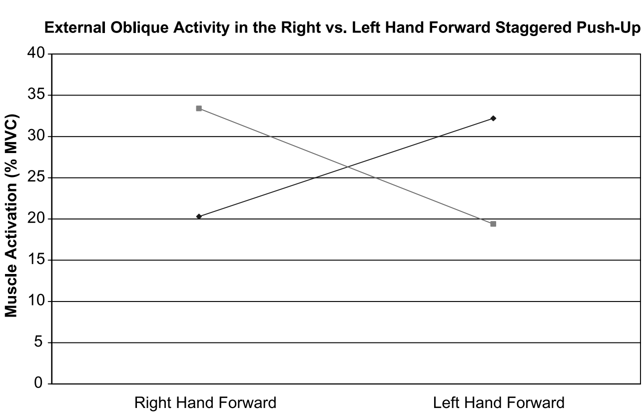

FIGURE 2—Performing the staggered hand placement push-up preferentially activates rectus abdominis and external oblique muscle on one side of the body. External oblique activity during a right hand forward and left hand forward push-up is shown.

RESULTS

Muscle activation levels for all exercises (shown in Table 1) are arranged from lowest to highest level of

TABLE 2. Total compression while performing push-ups (see Fig.1 for description).

Pushup	Compression (N)
Standard	1838
Slow eccentric	2222
Left hand on ball	2295
Right hand on ball	2315
Staggered hands—left forward	2337
Staggered hands—right forward	2532
Hand on two balls (one on each)	2829
Two hands on one ball	2840
Fast concentric	3905
Clapping	4699
One arm	5848
Alternating	6224

activation. The more demanding dynamic push-ups required higher muscle activation. Paired *t*-tests were performed to compare right and left rectus abdominis, external oblique, and internal oblique (IO) for ball and staggered hand push-ups. Those interested in spine stability will note how the staggered hand push-up caused a switch in dominance from the right- and left-side RA and EO (Fig. 2). Right RA activation was significantly higher than left RA activation during the left hand forward push-up, and vice versa for the right hand forward push-up ($P < 0.001$). EO also demonstrated a switch in dominance for the staggered hand position push-ups ($P < 0.01$). Thus, the staggered push-up preferentially activates the muscles unilaterally while maintaining enough three-dimensional moment to maintain the neutral spine posture. Spine compression for each exercise (Table 2) shows that the one-arm push-up loads the spine in compression to the highest level observed, whereas performing push-ups on the labile balls is relatively

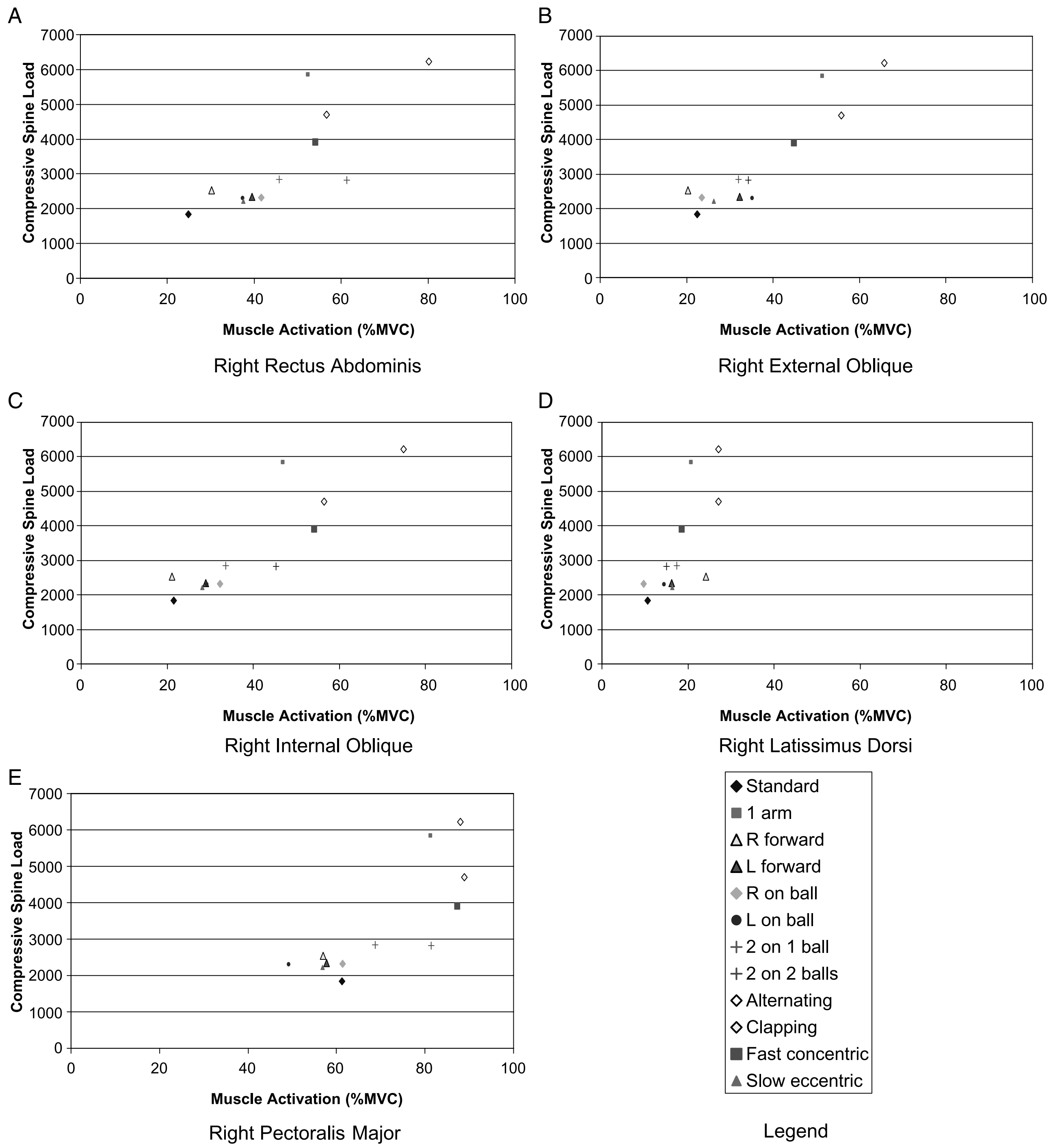

FIGURE 3—(A–E): Spine compression from performing a specific style of push-up, together with the activation of individual muscles, guides the reader in making appropriate progressions of exercise for the individual. For example, placing the hand on balls activates rectus abdominis muscle without substantial increases in spine compression.

spine conserving. The resultant spine compression versus specific muscle activation level for each exercise (shown in Fig. 3) FS is useful in guiding appropriate exercise progression. For example, if one is seeking exercise to target the abdominals and spare the spine from high compressive loads, then performing push-ups on the labile balls could be recommended. They create higher muscle activation but relatively low spine compression. Some "skill" differential was noted between participants during the ballistic push-up exercises in terms of muscle-force sequencing. Although this was not a central part of the study, these observations were interesting. Some participants had very tightly synchronized force development of the abdominal and shoulder musculature (interestingly, the best was the professional football player) in a "plyometric" fashion. In contrast, a less skilled participant (graduate student) contracted muscle over a broader length of time and was not able to synchronize force development (Fig. 4).

DISCUSSION

Although performing push-ups with the hands on labile surfaces has some effect on spine load, the one-arm and more ballistic forms of the exercise requiring the hands to move are much more spine demanding. Those interested in challenging the abdominal obliques and "steering" the

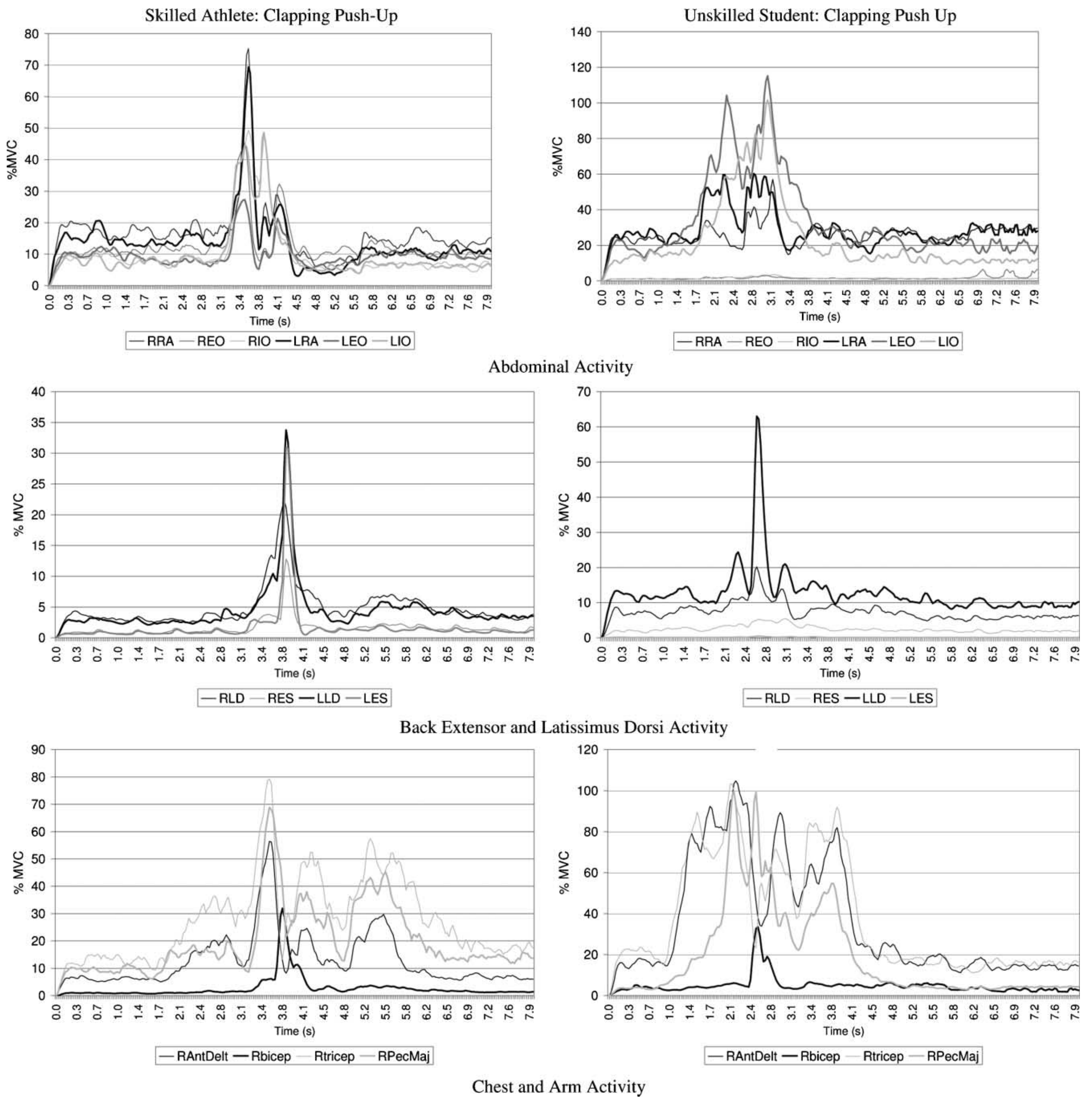

FIGURE 4—Linear envelope electromyelographic (EMG) time histories of the professional athlete (left side) demonstrated skill in coordinating muscle activity into a plyometric burst. In contrast, a less skilled participant (right side) did not demonstrate optimal muscle activity coordination, given the broader length of time over which the abdominal and arm musculature reach peak activity.

asymmetric force from staggered hand placement through the torso will be interested in the modest increase in spine compression demand. Not surprisingly, the plyometric forms of the push-ups are much more muscularly demanding and, therefore, result in higher spine load. This may be a concern for those who are sensitive to spine compression during provocative diagnostic testing. Spinal loading during many forms of the push-up is substantial. Little wonder that they are problematic for some painful backs. On the other hand, they may be very appropriate as an abdominal plyometric exercise for high-performance individuals.

Because of the limited amount of previous research performed on this topic, it is only possible to integrate a few of the findings of this study with previously published research. The muscle activation patterns of push-up exercises involving ballistic contractions represent a typical plyometric pattern that may be beneficial to individuals involved in performance training or rehabilitation because it is thought to improve proprioception and kinesthesisa, both of which are essential to functional stability (11). The observations of Reaper et al. (11) suggest participants adapted to performing specific plyometric exercises. They were able to utilize stored elastic energy more efficiently and increase motor unit recruitment while increasing coordinated muscle firing. Although this study did not quantify elastic energy, it appears that highly trained individuals were better able to produce synchronized peak muscle activity. Performing exercises on a labile surface increased torso cocontraction relative to a stable surface because it posed a greater threat of falling when compared with performance on a stable surface (4). Previously, Vera-Garcia et al. (12) observed an increase in torso activation when performing curl-ups on a labile versus stable surface. Nonetheless, the labile surface variations tested here required the participants to "steer" the hand forces through the torso linkage, which would be very desirable training for some.

Assumptions were made in calculating spine load in this study. It was assumed that a neutral lumbar spine and semiprone posture was maintained throughout the entire protocol of push-up trials. This was monitored and appears to be reasonable. Thus, variations in spine compression should be dominated by muscular sources. The results are also based on the average muscle response of our participants, and individual variation was not considered, nor was it the purpose of the study. All participants were relatively physically fit. The results of this study may not be generalizable to the majority of the population.

Clinical implications. Exercise selection is governed by the current capabilities of the individual, that person's particular injury history, loading tolerance, and training objectives. These data should assist those in selecting optimal progressions that involve labile surfaces and dynamic forms of the push-up for general training through to more progressive plyometric forms of the push-up exercise.

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