Core Muscle Activation in Suspension Training Exercises

Article *in* Journal of Human Kinetics · March 2017

DOI: 10.1515/hukin-2017-0023

Giovanni Cugliari
Università degli Studi di Torino

Gennaro Boccia
Università degli Studi di Torino

Journal of Human Kinetics volume 56/2017, 61-71 DOI: 10.1515/hukin-2017-0023

Section I – Kinesiology

DE GRUYTER OPEN

Core Muscle Activation in Suspension Training Exercises

by

Giovanni Cugliari[1,2], Gennaro Boccia[3,4]

A quantitative observational laboratory study was conducted to characterize and classify core training exercises executed in a suspension modality on the base of muscle activation. In a prospective single-group repeated-measures design, seventeen active male participants performed four suspension exercises typically associated with core training (roll-out, bodysaw, pike and knee-tuck). Surface electromyographic signals were recorded from lower and upper parts of rectus abdominis, external oblique, internal oblique, lower and upper parts of erector spinae muscles using concentric bipolar electrodes. The average rectified values of electromyographic signals were normalized with respect to individual maximum voluntary isometric contraction of each muscle. Roll-out exercise showed the highest activation of rectus abdominis and oblique muscles compared to the other exercises. The rectus abdominis and external oblique reached an activation higher than 60% of the maximal voluntary contraction (or very close to that threshold, 55%) in roll-out and bodysaw exercises. Findings from this study allow the selection of suspension core training exercises on the basis of quantitative information about the activation of muscles of interest. Roll-out and bodysaw exercises can be considered as suitable for strength training of rectus abdominis and external oblique muscles.

Key words: *core stability, core strength, electromyography, abdominal muscles.*

Introduction

In recent years, core training has been widely studied since it has been considered a pivotal issue in health, rehabilitation and sports performance (Hibbs et al., 2008). However, the definition of the core varies with the interpretation of the literature (Hibbs and Thompson, 2008). Anatomically, the core region has been described as the area bounded by the abdominal muscles in the front, by paraspinal and gluteal muscles in the back, by diaphragm on the top and by pelvic floor and girdle musculature at the bottom (Richardson et al., 1999). The core represents the connection between lower and upper limbs and should be considered as a functional unit in which different muscles interact, even if not located in the thoraco-lumbar region (such as shoulders and pelvic muscles). However, literature concerning core training sometimes fails to distinguish between concepts of core stability and core strength. Faries and Greenwood (in Hibbs and Thompson, 2008) formulated the following clear definitions: core stability refers to the ability to stabilize the spine as a result of muscle activity, while core strength refers to the ability of muscles' contractions to produce and transfer force as a result of muscle activity. Since strength and motor control are complementary qualities, the core training programmes can target mainly, but not exclusively, at muscle strengthening and/or motor control of core musculature. Motor control training seems to require low intensity

[1] - *Department of Brain and Behavioral Sciences, Unit of Medical and Genomic Statistics, University of Pavia, Italy..*
[2] - *Department of Medical Sciences, University of Torino, Torino, Italy.*
[3] - *CeRiSM Research Center "Sport, Mountain, and Health", Rovereto, (TN), Italy.*
[4] - *Motor Science Research Center, School of Exercise & Sport Sciences, SUISM, Department of Medical Sciences, University of Turin. 12, Torino, Italy.*

Authors submitted their contribution to the article to the editorial board.
Accepted for printing in the Journal of Human Kinetics vol. 56/2017 in March 2017.

stabilization exercises focused on efficient integration of low threshold recruitment of local and global muscle systems. Conversely, core strength training seems to require high intensity and overload training of the global muscle system. Vezina and Hubley-Kozey (2000) suggested that core stability programmes should include muscle activation below 25% of maximum voluntary contraction (MVC), while core strength training should include activation higher than 60% of MVC to result in strength benefits.

The available evidence suggests that to adequately train the core muscles in athletes, strength and conditioning specialists should focus on implementing multi-joint full body exercises, rather than core-specific exercises (Martuscello et al., 2013). Exercises involving the full body linkage such as plank exercises, have been advocated to enhance the capacity of transmitting force through the body linkage (Schoenfeld et al., 2014). Training with labile systems has been documented to offer unique opportunities for linkage training challenges (McGill et al., 2015). Several studies examined core muscle activation during the execution of various exercises on stable and unstable surfaces (for a review see: Behm et al., 2010). The use of unstable surfaces contacting the subject's feet or hands is becoming popular in strength training. Instability can be obtained through the use of many devices and techniques including, but not limited to, unstable platforms such as Bosu or Swiss balls. More recently, suspension training systems have been added to the list of instability training devices.

In suspension training, lower or upper limbs are hung with straps free to oscillate. Many core directed exercises are designed with such a device, creating a wide variety of challenges. These exercises consist of multi-planar and multi-joint movements, and are executed with complex techniques. It is important to quantify the muscle contraction intensity since it is a key factor in establishing training effects induced by this sort of exercises. Although considerable research has examined more traditional means of instability training (Behm and Drinkwater, 2010), little previous research has evaluated the effects of suspension training on muscle activation. In particular, some studies focused on core-directed exercises (Atkins, 2014; Byrne et al., 2014; Czaprowski et al., 2014; Mok et al., 2014; Snarr and Esco, 2014), whereas others investigated the effect of the application of suspension system on core muscle activity in push exercises (Calatayud et al., 2014; McGill et al., 2014; Snarr and Esco, 2013). Further investigation of these exercise approaches is needed to understand their influence on muscle activation and joint load levels.

The primary purpose of this study therefore, was to examine differences in core muscle activation across four full-body linkage exercises using a suspension training system. These exercises were chosen from a spectrum of whole body linkage exercises focused on the anterior core musculature executed in instable conditions, including a roll-out, bodysaw, pike, and knee-up. Although the selected exercises were mainly focused on anterior slings, we wanted to provide a comprehensive view of core muscle activation by monitoring rectus abdominis, internal and external oblique, and paraspinal muscles. It was hypothesized that significant differences would be found in core muscles among exercises. The second aim of the study was to determine which of these exercises would reach the threshold of 60% of MVC, expected to be high enough to increase muscle strength. It was hypothesized that the four exercises would elicit muscle activity in excess of 60% of MVC in the rectus abdominis, i.e. the muscle on which the main focus was put considering the selected exercises.

Material and Methods

Seventeen healthy participants were recruited (age 27.3±2.4 years, body height 172±5 cm, body mass 69.2±9.3 kg). All participants were physically active, declaring three practice sessions per week of resistance training. The participants had no prior experience with suspension training exercises. Inclusion criteria for study participation were as follows: no past or present neurological or musculoskeletal trunk or limb pathology, no cardiorespiratory disease, no history of abdominal, shoulder or back surgery, and no psychological problems. Participants were instructed to refrain from performing strenuous physical activity in the 24 hours preceding all experimental sessions. All participants signed a written informed consent form. The study was previously approved by the research ethics committee of the Department of Medical Sciences, University of Turin.

The surface electromyographic (EMG) signals were obtained from six trunk muscles with concentric bipolar electrodes (CoDe, Spes Medica, Battipaglia, Italy). Before the placement of the electrodes, the skin was slightly abraded with adhesive paste and cleaned with water in accordance to SENIAM recommendation for skin preparation (Hermens et al., 2000). The electrodes were placed according to the instructions described in previous methodological works (Beretta Piccoli et al., 2014; Boccia and Rainoldi, 2014) – lower rectus abdominis: on the lower part of the rectus abdominis, 3 cm lateral to the midline; upper rectus abdominis: on the upper part of the rectus abdominis, 3 cm lateral to the midline; external oblique: 14 cm lateral to the umbilicus, above the anterior superior iliac spine (ASIS); internal oblique: 2 cm lower with respect to the most prominent point of the ASIS, just medial and superior to the inguinal ligament; lower erector spinae: 2 cm lateral to the L5-S1; upper erector spinae: 6 cm lateral to the L1-L2. The electrodes were placed only on the left (randomly chosen) side of the body; the reference electrode was positioned on the wrist.

The signal of a biaxial electrogoniometer (SG 150, Biometrics Ltd, Gwent, UK) positioned at the level of the shoulders (for the roll-out and bodysaw) or the hips (for the pike and knee-tuck), depending on which joint was more involved during the exercise, was used as a trigger to highlight exercise repetitions. The electrodes were fixed using extensible dressing (Fixomull®, Beiersdorf). The EMG signals were synchronized with the electrogoniometer signal, amplified (EMG-USB, OT Bioelettronica, Torino, Italy), sampled at 2048 Hz, bandpass filtered (3-dB bandwidth, 10- 450 Hz, 12 dB/oct slope on each side), and converted to digital data by a 12-bit A/D converter. Samples were visualized during acquisition and then stored in a personal computer using OT BioLab software (version 1.8, OT Bioelettronica, Torino, Italy) for further analysis.

The participants recruited were instructed with regard to the correct technique of suspension exercise and the MVC procedure during the first experimental session conducted one week before the measurement session. The participants were asked to refrain from physical activity 24 hours before the measurements. During the measurement session, participants performed 4 exercises with the use of suspension straps (TRX® suspension trainer; Fitness Anywhere LCC, San Francisco, CA, USA) in random order. The exercises were selected based on a previous study (Behm and Drinkwater, 2010) that indicated them as important in developing core strength.

At the beginning of the measurement session, three MVC exercises were performed twice for 5 s, with 2 min rest between them. The following standardized exercises (Ng et al., 2002) were used to activate maximally the trunk muscles (Figure 1):

1. Upper rectus abdominis (URA) and lower rectus abdominis (LRA): body supine with hips and knees flexed 90°, with feet locked. Participants flexed the trunk (i.e. crunch execution) against resistance at the level of the shoulders;
2. External oblique (EO) and internal oblique (IO): side-lying with the hip at the edge of the bench and feet locked by a second operator. Participants performed side-bend exercise against resistance at the level of the shoulder;
3. Lower erector spinae (LES) and upper erector spinae (UES): prone position with ASIS at the edge of the bench and feet locked by a second operator. Participants performed a back extension against resistance at the level of the shoulders.

The suspension system handles were positioned 15 cm from the ground. Participants were required to achieve a range of motion with the correct technique execution and to maintain a neutral position of the spine and pelvis in each exercise. A certified strength and conditioning coach monitored the exercise performance to ensure that the exercise was properly executed considering its technique. Each exercise was repeated three times and lasted 6 s. A metronome set at 30 beats per minute was used to ensure proper timing (with 4 beats for each repetition): 2 s from the initial position to the final position (concentric phase); 2 s of maintenance (isometric phase); and 2 s returning to the starting position (eccentric phase). The exercises were performed with 3 min of rest in-between to allow complete recovery. The random order of the exercises allowed to mitigate the effects of cumulative fatigue on EMG estimates. Each session lasted approximately 90 min. The following exercises were used (Figure 2):

1) Roll-out: participants assumed an inclined standing position while placing each hand on the strap handles, with elbows and wrists placed below the shoulders, arms perpendicular to the floor and shoulders flexed approximately 45°; they then performed a shoulder flexion moving the hands forward;

2) Bodysaw: participants assumed a prone position, they placed elbows below the shoulders, both forearms touching the floor, while placing each foot on the strap handle; participants then flexed the shoulders and extended the elbows pushing the body backwards;

3) Pike: participants assumed a push-up position with the feet in strap handles, then they flexed hips to approximately 90°, while keeping the knees fully extended;

4) Knee-tuck: participants assumed a push-up position while placing each foot in the strap handle, then they flexed both hips and knees to approximately 90°, bringing the knees forward.

The average rectified value (ARV) of EMG signals was computed off-line with numerical algorithms using non-overlapping signal epochs of 0.5 s (Hibbs et al., 2011). The epoch with the highest ARV was chosen as reference in the MVCs. The second and third repetitions of each exercise were analyzed. The mean value of ARV over the two repetitions was calculated for each muscle and normalized with respect to the maximum ARV obtained during the correspondent MVC.

The normality assumption of the data was evaluated with the Shapiro-Wilk test; homoscedasticity and autocorrelation of the variables were assessed using the Breusch-Pagan and Durbin-Watson tests. The differences between exercises (pike – bodysaw – knee-tuck – roll-out) and between muscles (LRA – URA – EO – IO – LES – UES) were compared with the 2-way analysis of variance (ANOVA). For the purpose of this report, only the results concerning differences between exercises were presented. For multiple comparisons, the Tukey test was used. The level of significance was set at $p < 0.01$. Statistical analyses were conducted using the R statistical package (version 3.0.3, R Core Team, Foundation for Statistical Computing, Vienna, Austria). Results are expressed as medians (Interquartile Range, IR).

Results

All participants managed to complete each exercise trial and thus, were included in the data analysis. Figure 3 shows the box plots of the activation values (% of MVC) of each muscle during the four exercises. Muscle activation (Median, IR) expressed as percentage values of ARV normalized to MVCs is reported in Table 1.

The normalized LRA activity was 140% (IR, 89%) of MVC during the roll-out, 100% (IR, 42%) of MVC during the bodysaw, 57% (IR, 36%) of MVC during the pike and 54% (IR, 50%) of MVC during the knee-tuck. The normalized LRA values were significantly higher ($p < 0.01$) during the roll-out and bodysaw compared to the pike and knee-tuck. The roll-out exercise showed significantly greater activation ($p < 0.01$) than the bodysaw.

The normalized URA activity was 67% (IR, 78%) of MVC during the roll-out, 57% (IR, 52%) of MVC during the bodysaw, 41% (IR, 48%) of MVC during the pike and 44% (IR, 41%) of MVC during the knee-tuck. The normalized URA values were significantly higher ($p < 0.01$) during the roll-out compared to the pike and knee-tuck.

The normalized EO activity was 71% (IR, 44%) of MVC during the roll-out, 59% (IR, 33%) of MVC during the bodysaw, 55% (IR, 21%) of MVC during the pike and 42% (IR, 7%) of MVC during the knee-tuck. The normalized EO values were significantly higher ($p < 0.01$) during the roll-out compared to the knee-tuck.

The normalized IO activity was 40% (IR, 31%) of MVC during the roll-out, 32% (IR, 20%) of MVC during the bodysaw, 23% (IR, 20%) of MVC during the pike and 18% (IR, 26%) of MVC during the knee-tuck. During all exercises the normalized IO values were not significantly higher ($p < 0.01$).

The normalized LES activity was 9% (IR, 5%) of MVC during the roll-out, 4% (IR, 3%) of MVC during the bodysaw, 12% (IR, 7%) of MVC during the pike and 8% (IR, 5%) of MVC during the knee-tuck. During all exercises the normalized LES values were not significantly higher ($p < 0.01$).

The normalized UES activity was 11% (IR, 6%) of MVC during the roll-out, 8% (IR, 6%) of MVC during the bodysaw, 9% (IR, 4%) of MVC during the pike and 6% (IR, 5%) of MVC during the knee-tuck. During all exercises the normalized UES values were not significantly higher ($p < 0.01$).

Table 2 shows the estimate (difference of means) at 95% of the confidence interval after Tukey multiple comparisons; in this case only "exercise factor" was considered.

The roll-out exercise showed significantly ($p < 0.01$) higher activation compared to the bodysaw (16%, CI 8-23%), pike (26%, CI 18-33%) and knee-tuck (29%, CI 21-37%). Pike and knee-tuck exercises showed significantly higher activation compared to the bodysaw of 10% (2-8%) and 13% (6-21%).

Figure 1

Standardized exercises used to maximally activate trunk muscles:
Lower rectus abdominis and upper rectus abdominis (left);
Internal oblique and external oblique (middle);
Lower erector spinae and upper erector spinae (right).

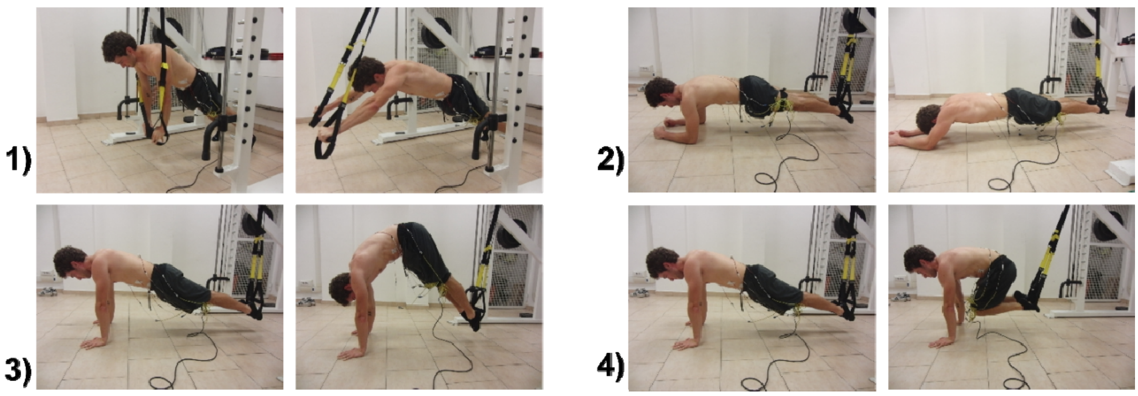

Figure 2

Initial and final positions of each exercise: 1) Roll-out; 2) Bodysaw; 3) Pike; 4) Knee-tuck.

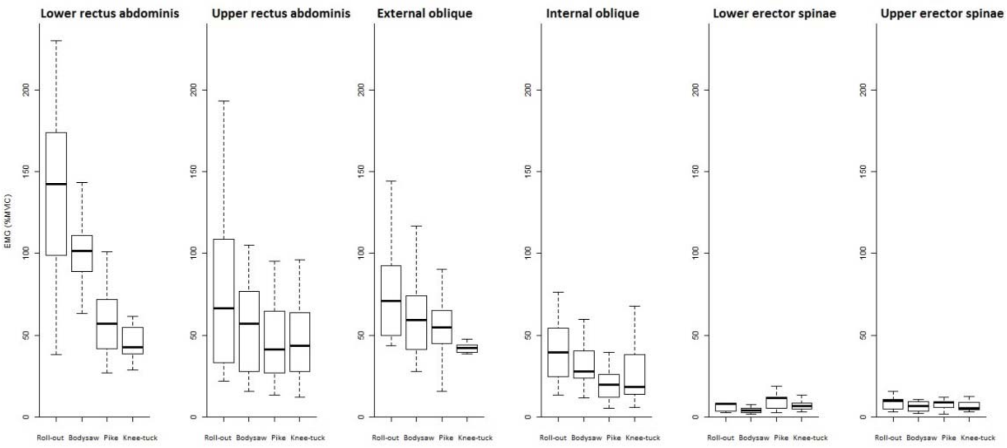

Figure 3
Each box plot shows the muscle activation (as percentage of maximum voluntary contraction) during exercise. Whiskers indicate variability outside the upper and lower quartiles.

Table 1
Muscle activation (Median, IR) expressed as percentage values of electromyographic amplitude normalized to maximum voluntary contraction. Results of the two-way ANOVA after Tukey multiple comparisons are reported as symbols; p<0.01.

	Lower rectus abdominis	Upper rectus abdominis	External oblique	Internal oblique	Lower erector spinae	Upper erector spinae
Pike	57 (36) ǂ §	41 (48) ǂ	55 (21)	23 (20)	12 (7)	9 (4)
Bodysaw	100 (42) ǂ Φ Ψ	57 (52)	59 (33)	32 (20)	4 (3)	8 (6)
Knee-tuck	54 (50) ǂ §	44 (41) ǂ	42 (7) ǂ	18 (26)	8 (5)	6 (5)
Roll-out	140 (89) § Φ Ψ	67 (78) Φ Ψ	71 (44) Ψ	40 (31)	9 (5)	11 (6)

Φ indicates statistically significant difference between the indicated exercise (explained in row) with respect to the pike
§ indicates statistically significant difference between the indicated exercise (explained in row) with respect to the bodysaw
Ψ indicates statistically significant difference between the indicated exercise (explained in row) with respect to the knee-tuck
ǂ indicates statistically significant difference between the indicated exercise (explained in row) with respect to the roll-out

Table 2

*Estimate at 95% of the confidence interval after Tukey multiple comparisons with the "exercise factor" considered. The estimate shows the difference of means (% of maximum voluntary contraction). * indicates the statistical significance of the adjusted p-value.*

Exercises	Estimate	Lower CI (95%)	Upper CI (95%)
Bodysaw – Roll-out	-16 *	-23	-8
Pike – Roll-out	-26 *	-33	-18
Knee-tuck – roll-out	-29 *	-37	-21
Pike – Bodysaw	-10 *	-18	-2
Knee-tuck – Bodysaw	-13 *	-21	-6
Knee-tuck – Pike	-3	-11	4

Discussion

Suspension training has become increasingly popular as a training tool. Despite this popularity, relatively little research exists on the effects of such training on muscle activation magnitude. The first objective of the study was to investigate the activation differences of four exercises (roll-out, bodysaw, pike and knee-tuck) to better characterize suspension training. Our findings indicate that suspension exercises could be an effective strategy to reach high to very high activation of abdominal muscles such as the rectus abdominis and external oblique.

To facilitate comparisons between exercises and previous studies, we categorized muscle activation into four levels according to previous studies, with <21% as low, 21–40% as moderate, 41–60% as high, and >60% as very high (Escamilla et al., 2010). Exercises used in the present study provide a range of medium to high intensity exercises through which participants or athletes can progress during a training or rehabilitation programme (Blanchard and Glasgow, 2014) (Figure 2). Roll-out exercise was the most challenging for core musculature, followed by bodysaw, pike and knee-tuck exercises (Table 2). The roll-out showed the highest activation of rectus abdominis and oblique muscles compared to other exercises. However, not all muscles responded in the same way across exercises. Although LRA showed much greater activation in roll-out and bodysaw compared to pike and knee-tuck exercises, the other muscles showed smaller differences. These findings could suggest that in the exercises characterized by shoulder flexion (such as roll-out and bodysaw), the increased requirement of core stability was reflected more by the lower rectus abdominis.

According to Vezina and Hubley-Kozey (2000), the exercises that generate muscle activity greater than 60% of MVC might be more conducive to developing muscular strength. The rectus abdominis (both parts) and EO reached activation higher than 60% of MVC (or very close to that threshold, 55%) in the roll-out and bodysaw; consequently these exercises can be considered suitable for strength training of these muscles. Although in the knee-tuck and pike, the rectus abdominis and EO did not reach the threshold of 60%, they presented high activation levels (41-60% MVC). While strengthening of the core is important, an activation level below 60% might be beneficial in increasing muscle endurance within the core. Since the core muscles are primarily composed of type I fibres (Haggmark and Thorstensson, 1979), muscular endurance should also be a major concern when designing strength and conditioning programmes (Vezina and Hubley-Kozey, 2000). Due to large demand for muscle activation, all the proposed exercises might be appropriate for extremely fit individuals in the latter stages of a progressive abdominal strengthening or rehabilitation programme.

Erector spinae muscles resulted in being activated at low and very low intensity. This is an expected result as all exercises focused on anterior abdominal wall muscles. This finding confirms that in the herein selected whole-body linkage exercises, the activation of core muscles can be mainly focused on abdominal muscles while keeping the paraspinal muscles involved with low intensity.

Although no direct comparison can be made between the selected suspension exercises compared to previously reported similar exercises, it is possible to highlight the following differences. We can compare only the activation of the rectus abdominis, since for oblique muscles we used a different normalization exercise than the other three studies. Plank exercises are frequently included in spine stabilization programmes as a means of improving motor control for spine stabilization. When plank exercises are performed on stable or unstable support surfaces, the reported activation level of the rectus abdominis and EO ranges from low to moderate (Garcia-Vaquero et al., 2012). When executed in suspension condition, rectus abdominis muscles also showed moderate activation (Byrne and Bishop, 2014). Only when the planks were performed with a similar technique (instability on lower limb and shoulder flexion) was the activation similar to that reported here, which was very high for the rectus abdominis (McGill and Andersen, 2015). Therefore, we can assume that our exercises were more challenging than an isometric plank in a stable condition.

In the roll-out, we found very high activation of LRA (140%) and URA (67%). These levels were higher than previously reported values obtained during the execution of the roll-out with the Swiss-ball (about 50-60% for rectus abdominis) (Escamilla and Lewis, 2010; Marshall and Desai, 2010) and similar to the values reported with the use of the Power Wheel, being very high for URA (76%) and LRA (81%) (Escamilla et al., 2006). In the pike, we found high activation of LRA (57%) and URA (41%). The values reported for the pike executed with the Swiss ball (Escamilla and Lewis, 2010) and Power Wheel (Escamilla and Babb, 2006) were similar for URA (Swiss ball 47%; Power Wheel 41%) and LRA (Swiss ball 55%; Power Wheel 53%). In the knee-tuck, we observed high activation of LRA (54%) and URA (44%). Otherwise, the values reported for the knee-tuck executed with the Swiss ball (Escamilla and Lewis, 2010) and Power Wheel (Escamilla and Babb, 2006) were lower for both URA (Swiss ball 32%; Power Wheel 41%) and LRA (Swiss ball 35%; Power Wheel 45%).

Our findings suggest that the two parts of the rectus abdominis can be activated differently according to the needs of the motor task (Kibler et al., 2006). This finding could be explained by the possibility to (voluntary or involuntary) modulate the activation ratio between rectus abdominis parts in order to achieve the best control of the core region. This could be justified by the metameric innervation of rectus abdominis muscles (Duchateau et al., 1988), although this issue is still controversial (Monfort-Panego et al., 2009). However, LRA muscles were generally more active than URA because of confounding methodological factors. MVCs of the LRA and URA in fact were estimated by a standardized exercise to activate maximally the trunk muscles: it could be argued that the same exercise fully activated URA whereas it failed to fully activate LRA. Hence, the EMG amplitude recorded during MVC was not the maximum achievable. Consequently, throughout experimental exercises, LRA seemed relatively more active than URA because its reference value of MVC was underestimated.

A few methodological limitations of our study warrant further consideration. In some cases, ARV estimates of EMG signals exceeded the MVC reference values (ARV higher than 100%). This inconsistency might be due to incomplete activation during MVC (as in the case of the lower rectus abdominis) and other confounding factors related to EMG technique (relative shift of muscle belly with respect to electrodes occurring in dynamic tasks and different activation between isometric and dynamic tasks, among others).

As widely reported, variability of muscular activation between participants was high. This suggests that performing these exercises, some individuals might produce more or less activation than the average activity indicated here. Although 17 individuals participated in this research, the differences in their fitness level and exercise experience could have affected the performance of the exercises and the resulting activation levels.

Crosstalk between muscles was minimized by using an innovative detection system based on concentric-ring electrodes which had been reported as having higher spatial selectivity compared to the traditional detection systems and reducing the problem of crosstalk from nearby muscles (Farina and Cescon, 2001).

Conclusions

Findings from this study, based on electromyographic analysis, showed that roll-out exercise was the most challenging. Moreover, roll-out and bodysaw exercises executed in suspension activated the rectus abdominis and external oblique muscles at intensities higher than, or very close to, 60% of the maximum voluntary contraction. Based on these findings, we can assume that roll-out and bodysaw exercises can be used to adequately strengthen the antero-lateral, superficial aspect of the core region, and thus they can be considered core strength exercises. These findings appear to have particular relevance for well-trained individuals given the high demand imposed by these exercises.

Acknowledgements

This work was supported by Funding for Innovation Projects under grant Project HExEC, PQR FESR 2007/1013

References

Atkins S. Electromyographic response of global abdominal stabilisers in response to stable- and unstable-base isometric exercise. *J Strength Cond Res,* 2015; 29: 1609-1615

Behm DG, Drinkwater EJ, Willardson JM, Cowley PM. The use of instability to train the core musculature. *Appl Physiol Nutr Metab,* 2010; 35: 91-108

Beretta Piccoli M, Rainoldi A, Heitz C, Wuthrich M, Boccia G, Tomasoni E, Spirolazzi C, Egloff M, Barbero M. Innervation zone locations in 43 superficial muscles: toward a standardization of electrode positioning. *Muscle Nerve,* 2014; 49: 413-21

Blanchard S, Glasgow P. A theoretical model to describe progressions and regressions for exercise rehabilitation. *Phys Ther Sport,* 2014; 15: 131-5

Boccia G, Rainoldi A. Innervation zones location and optimal electrodes position of obliquus internus and obliquus externus abdominis muscles. *J Electromyogr Kinesiol,* 2014; 24: 25-30

Byrne JM, Bishop NS, Caines AM, Crane KA, Feaver AM, Pearcey GE. Effect of using a suspension training system on muscle activation during the performance of a front plank exercise. *J Strength Cond Res,* 2014; 28: 3049-55

Calatayud J, Borreani S, Colado JC, Martin FF, Rogers ME, Behm DG, Andersen LL. Muscle Activation during Push-Ups with Different Suspension Training Systems. *J Sports Sci Med,* 2014; 13: 502-10

Czaprowski D, Afeltowicz A, Gebicka A, Pawlowska P, Kedra A, Barrios C, Hadała M. Abdominal muscle EMG-activity during bridge exercises on stable and unstable surfaces. *Phys Ther Sport,* 2014; 15: 162-8

Duchateau J, Declety A, Lejour M. Innervation of the rectus abdominis muscle: implications for rectus flaps. *Plastic and reconstructive surgery*, 1988; 82: 223-8

Escamilla RF, Babb E, DeWitt R, Jew P, Kelleher P, Burnham T, Busch J, D'Anna K, Mowbray R, Imamura RT. Electromyographic analysis of traditional and nontraditional abdominal exercises: implications for rehabilitation and training. *Phys Ther*, 2006; 86: 656-71

Escamilla RF, Lewis C, Bell D, Bramblet G, Daffron J, Lambert S, Pecson A, Imamura R, Paulos L, Andrews JR. Core muscle activation during Swiss ball and traditional abdominal exercises. *J Orthop Sports Phys Ther*, 2010; 40: 265-76

Farina D, Cescon C. Concentric-ring electrode systems for noninvasive detection of single motor unit activity. *IEEE Trans Biomed Eng*, 2001; 48: 1326-34

Garcia-Vaquero MP, Moreside JM, Brontons-Gil E, Peco-Gonzalez N, Vera-Garcia FJ. Trunk muscle activation during stabilization exercises with single and double leg support. *J Electromyogr Kinesiol*, 2012; 22: 398-406

Haggmark T, Thorstensson A. Fibre types in human abdominal muscles. *Acta Physiol Scand*, 1979; 107: 319-25

Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol*, 2000; 10: 361-74

Hibbs AE, Thompson KG, French D, Wrigley A, Spears I. Optimizing performance by improving core stability and core strength. *Sports Med*, 2008; 38: 995-1008

Hibbs AE, Thompson KG, French DN, Hodgson D, Spears IR. Peak and average rectified EMG measures: which method of data reduction should be used for assessing core training exercises? *J Electromyogr Kinesiol*, 2011; 21: 102-11

Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. *Sports Med*, 2006; 36: 189-98

Marshall PW, Desai I. Electromyographic analysis of upper body, lower body, and abdominal muscles during advanced Swiss ball exercises. *J Strength Cond Res*, 2010; 24: 1537-45

Martuscello JM, Nuzzo JL, Ashley CD, Campbell BI, Orriola JJ, Mayer JM. Systematic review of core muscle activity during physical fitness exercises. *J Strength Cond Res*, 2013; 27: 1684-98

McGill S, Andersen J, Cannon J. Muscle activity and spine load during anterior chain whole body linkage exercises: the body saw, hanging leg raise and walkout from a push-up. *J Sports Sci*, 2015; 33: 419-26

McGill SM, Cannon J, Andersen JT. Analysis of pushing exercises: muscle activity and spine load while contrasting techniques on stable surfaces with a labile suspension strap training system. *J Strength Cond Res*, 2014; 28: 105-16

Mok NW, Yeung EW, Cho JC, Hui SC, Liu KC, Pang CH. Core muscle activity during suspension exercises. *J Sci Med Sport*, 2015; 18: 189-94

Monfort-Panego M, Vera-Garcia FJ, Sanchez-Zuriaga D, Sarti-Martinez MA. Electromyographic studies in abdominal exercises: a literature synthesis. *J Manipulative Physiol Ther*, 2009; 32: 232-44

Ng JK, Kippers V, Parnianpour M, Richardson CA. EMG activity normalization for trunk muscles in subjects with and without back pain. *Med Sci Sports Exerc*, 2002; 34: 1082-6

Richardson C, Jull P, Hodges J. Therapeutic exercise for spinal segmental stabilization in low back pain: scientific basis and clinical approach. *J Can Chiropr Assoc*, 2000; 44: 125

Schoenfeld BJ, Contreras B, Tiryaki-Sonmez G, Willardson JM, Fontana F. An electromyographic comparison of a modified version of the plank with a long lever and posterior tilt versus the traditional plank exercise. *Sports Biomech*, 2014; 13: 296-306

Snarr RL, Esco MR. Electromyographic comparison of traditional and suspension push-ups. *J Hum Kinet*, 2013; 39: 75-83

Snarr RL, Esco MR. Electromyographical comparison of plank variations performed with and without instability devices. *J Strength Cond Res*, 2014; 28: 3298-305

Vezina MJ, Hubley-Kozey CL. Muscle activation in therapeutic exercises to improve trunk stability. *Arch Phys Med Rehabil*, 2000; 81: 1370-9

Corresponding author:
Gennaro Boccia,
1) CeRiSM Research Center "Sport, Mountain, and Health", via del Ben 5/b, 38068, Rovereto, (TN), Italy.
2) Motor Science Research Center, School of Exercise & Sport Sciences, SUISM, Department of Medical Sciences, University of Turin. 12, piazza Bernini, 10143, Torino, Italy.
Address: 12, piazza Bernini, 10143, Torino, Italy;
Telephone: +39 0117764708
Fax: +39 011748251
E-mail gennaro.boccia@unito.it