Technology and Health Care 26 (2018) 401–407
DOI 10.3233/THC-171051
IOS Press

Best core stabilization exercise to facilitate subcortical neuroplasticity: A functional MRI neuroimaging study

Do Hyun Kim[a], Jae Jin Lee[b] and Sung (Joshua) Hyun You[b,*]
[a]*HIP and MAL Laboratory, Department of Rehabilitation Science, Inje University, Gimhae, Korea*
[b]*Institute of Sports Movement Artificial-Intelligence Technology, Department of Physical Therapy, Yonsei University, Wonju, Korea*

Received 29 August 2017
Accepted 27 January 2018

Abstract.
OBJECTIVE: To investigate the effects of conscious (ADIM) and subconscious (DNS) core stabilization exercises on cortical changes in adults with core instability.
PARTICIPANTS: Five non-symptomatic participants with core instability.
METHODS: A novel core stabilization task switching paradigm was designed to separate cortical or subcortical neural substrates during a series of DNS or ADIM core stabilization tasks.
RESULTS: fMRI blood BOLD analysis revealed a distinctive subcortical activation pattern during the performance of the DNS, whereas the cortical motor network was primarily activated during an ADIM. Peak voxel volume values showed significantly greater DNS (11.08 ± 1.51) compared with the ADIM (8.81 ± 0.21) ($p = 0.043$).
CONCLUSION: The ADIM exercise activated the cortical PMC-SMC-SMA motor network, whereas the DNS exercise activated both these same cortical areas and the subcortical cerebellum-BG-thalamus-cingulate cortex network.

Keywords: Core stabilization, brain activation, fMRI, subcortical structure

1. Background

Core stabilization is a subconscious, coordinated core muscle activation to maintain an optimal postural alignment for dynamic upper and lower extremity movement, such as reaching and locomotion [1]. Core stabilization is genetically determined and programmed in the central nervous system (CNS) in humans [2] and involves coordinated feedforward activation of deep core muscles (diaphragm, transversus abdominis, multifidus, and pelvic floor) and global muscles prior to any purposeful movement [3]. Neurodevelopmentally, infants automatically learn to lift their heads up and pull up their legs and develop sagittal stabilization of the spine and chest, which become a punctum fixum or a stabilization point

*Corresponding author: Sung (Joshua) Hyun You, Movement Healing Laboratory, Department of Physical Therapy, Yonsei University, 1 Yonsei Dae Kil, Wonju City, Kangwon-do, 220-710, Korea. Tel.: +82 33 760 2476; E-mail: neurorehab@yonsei.ac.kr.

for subsequent dynamic rolling and turning movement [4]. If this core stabilization is improperly developed, the infant may compensate with abnormal movement, as seen in children with cerebral palsy (CP) or central coordination disorder or in adults with musculoskeletal conditions (e.g., low back pain) [5,6].

Recently, the abdominal drawing-in maneuver (ADIM) and the dynamic neuromuscular stabilization (DNS) have been recognized as exercises that can provide optimal spinal stability, reduce back pain [7], and improve balance [8]. The ADIM involves conscious and selective activation of the transverse abdominal and internal oblique muscles to enhance segmental lumbar spinal stability by actively and posteriorly drawing the belly into the spine [9]. Haruyama el al. [10] investigated the effects of 4 weeks of ADIM training on trunk function and standing balance in sub-acute stroke patients. The results showed that Trunk Impairment Scale, Functional Reach test, Timed Up-and-Go test, and Functional Ambulation Categories scores were significantly improved when compared to conventional neurodevelopment treatment (NDT).

On the other hand, the DNS utilizes subconscious and synkinetic activation of deep core muscles (diaphragm, transversus abdominis, multifidus, and pelvic floor) and global muscles to generate the optimal intra-abdominal pressure (IAP) and associated entire uprighting spinal stability [7]. In fact, a recent clinical study demonstrated a superior effect of DNS on core muscle activation over the conventional NDT in sub-acute stroke patients. Specifically, transverse abdominal and internal oblique muscles electromyographic activity was significantly greater in the DNS group than the NDT group, supporting the notion that the subconscious core stabilization method is more beneficial for deep core muscle activity control [11].

Despite the fact that both core stabilization exercises have been clinically proven to be effective, the underlying neural control mechanisms remain unknown. Over the last several decades, neuroimaging researches have studied to investigate the potential neurological mechanisms concerning core stabilization via electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) [12]. To date, only one case study has examined a potential neural mechanism of ADIM using fMRI. In that case study, the primary motor cortex, the somatosensory cortex, association areas, and the frontal cortex were activated during performance of ADIM [12], suggesting that the ADIM involves a conscious neural motor network. Nevertheless, neural control mechanisms during conscious ADIM and subconscious DNS core stabilization exercises have yet to be elucidated.

Therefore, the specific purpose of this study was to investigate the effects of conscious (ADIM) and subconscious (DNS) core stabilization exercises on changes in the neural (cortical and subcortical) control mechanisms and network in adults with core instability. We hypothesized that different neuroplastic mechanisms are involved in conscious (ADIM) and subconscious (DNS) core stabilization exercises. Clinically, this advanced fMRI neuroimaging technology enabled us to better understand neurophyisological mechanism and thus provides the important core stabilization exercise regimen and guidelines for clinicians in adults with core instability.

2. Methods

2.1. Participants

Asymptomatic five participants with core instability (mean age: 24.20 ± 2.38 years; mean height: 164.40 ± 11.41 cm; mean weight: 60.52 ± 10.68 kg) were recruited for the experimental study. The study was approved by the Institutional Review Board of Yonsei University (2012–09) and was conducted in accordance with the Declaration of Helsinki. Informed consent was obtained from all participants prior to their participation. Core instability was defined as an inability to stabilize the target pressure level (64–70 mmHg) during the straight leg lowering test [13]. Participants who had any known history of neurological or musculoskeletal disorders or claustrophobia were excluded from the study.

2.2. Experimental procedures

All participants underwent a pre-health screening, core instability test, four core stabilization exercises, and fMRI imaging tests. The pre-health screening was performed to rule out any known history of neurological (e.g., seizure) or musculoskeletal (e.g., back pain) disorders or claustrophobia.

2.2.1. Core instability test

Participants were instructed to lie in a supine position with a 90–90° hip and knee flexion position, and the pressure biofeedback unit (PBU) was placed under the participant's lumbar region. The PBU was inflated to 70 mmHg, and participants were asked to maintain a neutral pelvic position and the target pressure range (64–70 mmHg) as they gradually lowered their legs toward the floor. If a participant was unable to lower both legs to the floor with the correct lumbopelvic posture and the target PBU pressure level, he or she is considered to have core instability.

2.2.2. Core stabilization exercises

All participants practiced two different core stabilization exercises for 30 minutes each day for three consecutive days. The core stabilization exercises consisted of conscious ADIM and subconscious DNS. During core stabilization training, real-time ultrasound imaging was used to provide precise visual feedback about the target muscle activation and thickness of the transverse abdominis (TrA), internal oblique (IO), and external oblique (EO). Ultrasound images were acquired using a SONOACE X8 (Medison Inc., Seoul, South Korea) with a 10-MHz linear 4.5 cm transducer (L5–12EC) using B mode (brightness) [13]. The transducer was oriented lateral to the midline and halfway between the iliac crest and the inferior border of the twelfth rib [14,15]. For the ADIM, participants were asked to lie in a hook-lying position and then to consciously pull the belly button into the spine while maintaining the target PBU pressure and a neutral lumbopelvic posture [9]. For the DNS, participants were first asked to stabilize their spines using DNS and then repetitively perform hip flexion and extension ranging from 70° to 90° while maintaining the 20 mmHg target pressure in the PBU placed under the opposite supporting heel [16].

2.3. Data processing and analysis

For measuring fMRI blood oxygen-level dependent (BOLD) signals, a 3 T Philips Achieva fMRI scanner (Philips, Amsterdam, the Netherlands) was used [17]. The block paradigm included 30 seconds of task duration and 30 seconds of rest duration at a frequency of 0.5 Hz and was repeated three times for each core stabilization task. The experimental sequence for the core stabilization exercise paradigms was assigned according to the block design (Fig. 1).

Functional images were acquired with an eight-channel phased array head coil in an axial orientation parallel to the anterior commissure – posterior commissure (AC – PC) line. A single-shot echo-planar imaging (EPI) sequence was used with a TR/TE of 3000/35 ms, a flip angle of 90°, a field of view (FOV) of 220×220 mm^2, a scan matrix of 80×79, a reconstruction matrix of 128×128, a slice thickness of 4 mm, and no gap. T1-weighted anatomic images were acquired in a conventional spin echo sequence, in which TR/TE = 385/10 ms, flip angle = 90°, FOV = 220×220 mm^2, scan matrix = 224×232 (reconstruction matrix = 512×512), and slice thickness = 4 mm, and the same slice positions as in the

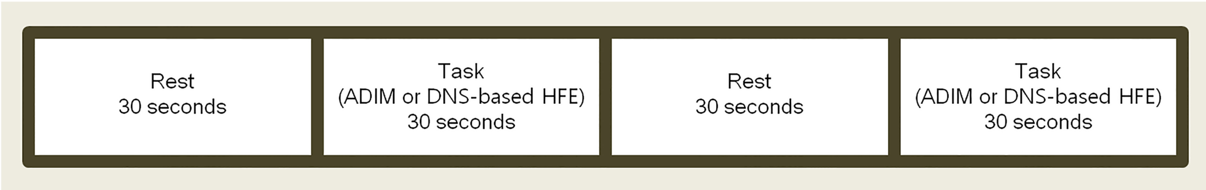

Fig. 1. fMRI experiment with a block design.

fMRI images were used. Acquired fMRI data were processed using SPM12 (Wellcome Department of Imaging Neuroscience, Institute of Neurology, London, England). The fMRI images were co-registered to each individual anatomical T1-weighted image. The fMRI images were then normalized to the Montreal Neurological Institute (MNI) standard space and spatially smoothed using an 8-mm full-width at half-maximum isotropic Gaussian kernel to adjust for individual anatomical differences.

We analyzed the whole brain as well as regions of interest (ROIs). The ROIs included both cortical areas, such as the primary motor cortex (PMC), somatomotor cortex (SMC), and supplementary motor area (SMA), and subcortical areas, such as the thalamus, basal ganglia (BG), and cerebellum, which are believed to modulate core stabilization movement. The fMRI images were analyzed using voxel-based morphometry implemented in the neuroimaging software SPM12 package (Wellcome Department of Imaging Neuroscience, Institute of Neurology, London, England). Voxel-based morphometry allows for voxel-wise comparison of the fMRI scan of the whole brain [18]. A Wilcoxon signed-rank test was performed to determine statistical differences in the voxel volumes of the ROIs between conscious ADIM and subconscious DNS-based HFE. For statistical analysis, PASW Statistics 20 (Norusis/SPSS Inc., Chicago, IL, USA) was used, and the statistical significance level was set at $\alpha = 0.05$.

3. Results

3.1. Cortical activation areas associated with ADIM and DNS core exercises

During the ADIM exercise, cortical activation areas were the PMC (topographically representing the trunk and abdomen), SMC, and SMA. During the DNS exercise, in addition to cortical activation in the PMC, SMC, and SMA areas, subcortical activation in the cerebellum, BG, thalamus, and cingulate cortex regions was observed.

3.2. Peak voxel volumes between the ADIM and DNS core exercises

A Wilcoxon signed-rank test showed significantly greater T-peak voxel volume values during the DNS (11.08 ± 1.51) compared with the ADIM (8.81 ± 0.21) ($p = 0.043$) (Table 1).

4. Discussion

The current investigation highlights novel neuroimaging evidence in neural substrates and networks underpinning two representative core stabilization paradigms (ADIM and DNS) in participants with core instability. To our knowledge, this is the first study to use an advanced fMRI experimental paradigm to evaluate whole brain function during dynamic core stabilization exercises. As hypothesized, fMRI data

Table 1
Brain activation in BOLD signal during ADIM and DNS

Subjects	ADIM					DNS					p
	MNI			Cluster size	T of	MNI			Cluster size	T of	
	x	y	z	(mm^3)	peak	x	y	z	(mm^3)	peak	
1	1.94	5.51	11.25	5926	8.92	−17.85	−25.59	−29.25	5125	9.67	
2	6.23	8.38	20.25	4656	8.45	−7.95	−60.30	−33.75	5293	10.14	
3	6.45	9.14	15.25	6025	9.01	−21.72	−25.58	−38.25	8679	13.52	0.043
4	9.53	4.51	21.75	4815	8.83	−15.21	−19.67	−40.25	5378	11.43	
5	9.67	4.52	30.25	5820	8.82	−15.23	−22.25	−30.75	5529	10.64	

demonstrated that the PMC, SMC, and SMA areas were primarily activated during the ADIM exercise, while the cortical PMC, SMC, and SMA and subcortical lateral part of the cerebellum, BG, and cingulate areas were activated during the DNS exercise. Most importantly, our fMRI results suggest that different neurophysiological mechanisms are involved in the regulation of core stabilization during the ADIM and DNS core exercise paradigms. Specifically, the present fMRI data associated with ADIM was consistent with only one case study, which examined cortical activation during ADIM in a patient with chronic low back pain. Moseley (2005) reported globalized cortical activation in the primary somatosensory cortex, anterior cingulate cortex, association areas (parietal cortex), and frontal cortex area during the ADIM exercise. While care should be taken when inferring from the fMRI data of a single subject, the previous finding suggests that, in this patient, cortical activation was altered due to pain physiology during the ADIM motor task despite the patient having no prior experience performing this task. In this sense, the fMRI results corroborated an earlier report that confirmed the occurrence of cognitive changes associated with pain in individuals with chronic low back pain (LBP) [12]. Nonetheless, further research is warranted to ascertain the exact neural mechanism.

On the other hand, during DNS, the anterior cingulate cortex, an integral part of the limbic system that might be involved with subcortical processing, learning, and memory [19] as well as core stabilization movement, executive function, and respiratory control, was activated. Unlike ADIM, which involves conscious, cortical motor control, the DNS exercise emphasizes subconscious and subcortical motor control of the diaphragm's dual respiratory and postural core stabilization functions. Fontes and colleagues (2005) reported distributed cortical and subcortical network activation in the primary sensorimotor cortex and cerebellum during a cycling exercise in seven healthy adults [20]. Similarly, Mehta and colleagues (2009) revealed that a pedaling motor task induced cortical and subcortical activation in the primary motor cortex and cerebellum compared with resting fMRI data [21]. The PMC, which was found to be activated during ADIM in this study, regulates conscious, explicit procedural motor learning. However, the cerebellum, which mediates automatic, subconscious, implicit motor learning [22], was activated during DNS. The other important subcortical networks activated during DNS included the BG and thalamus. The BG-thalamus-cerebellum network might play an important role in procedural knowledge and learning, as evident during the DNS core stabilization exercise. It is plausible that the thalamic ventral lateral nucleus modulates core muscle activation and the learning process while interacting with cortical (SMA, PMC, anterior cingulate cortex) and subcortical targets (BG and cerebellum) [23].

Taken together, unlike the previous work, the present study contributed to the current body of knowledge by means of identifying neural mechanisms for core stabilization exercises using a new fMRI paradigm. The current fMRI experimental method provided a superior neuroimaging result to better distinguish the difference in the neural network and mechanism than the previous work done by Moseley. This finding has an important clinical ramification for neurological patients with stroke and CP to improve core and postural stabilization which are essential for balance and locomotor rehabilitation. For example, the DNS core stabilization exercise can be applied for subcortical, implicit motor relearning in stroke and CP patients whose cortical network (SMC and PMC) is impaired, but the subcortical network is relatively is spared. On the other hand, the ADIM core stabilization exercise may be more beneficial for cortical, explicit relearning in neurological patients whose subcortical network (BG, thalamus, brainstem, and cerebellum) is compromised and yet the cortical area is spared. Therefore, depending on the cortical or subcortical brain lesion, the type of the core stabilization exercise should be carefully selected accordingly to maximize the effective rehabilitation outcomes.

This study contained some limitations that should be considered for future research. One limitation involves the head motion associated with core stabilization movement tasks, which might affect neuronal activation [24]. To minimize any potential effects of the head motion artifact, we applied digital motion correction and realigned the images to produce the optimal corrected images, with a motion variation of less than 1 mm. While motion-corrected images should be interpreted with caution, the fMRI resolution procedure used in this study was sufficient to adequately identify the regions of cortical and subcortical activation. The other limitation was that the present study was a preliminary investigation, which invites a further study with a larger sample size.

5. Conclusion

The present investigation demonstrated a novel fMRI experimental paradigm to decipher the underlying neural substrates during core stabilization exercises. fMRI experimental analysis showed somewhat distinct brain activation patterns between the ADIM and DNS core stabilization exercises. The ADIM exercise activated the cortical PMC-SMC-SMA motor network, whereas the DNS exercise activated both these same cortical areas and the subcortical cerebellum-BG-thalamus-cingulate cortex network. Most importantly, the present fMRI findings provide clinical insight that different types of core stabilization exercises utilize either cortical or subcortical motor control networks, which should be considered when designing a core stabilization exercise program in individuals with cortical or subcortical lesions. Nevertheless, the future research should be implemented to examine the effects of the core stabilization exercises on neural control mechanisms and associated core stability function in other larger pathological populations (e.g., back pain, stroke) with core instability to generalize our current findings.

Conflict of interest

None to report.

References

[1] Ryerson S, Byl NN, Brown DA, Wong RA, Hidler JM. Altered trunk position sense and its relation to balance functions in people post-stroke. J Neurol Phys Ther. 2008; 32: 14-20.

[2] Pang MY, Yang JF. Interlimb co-ordination in human infant stepping. J Physiol. 2001; 533: 617-625.

[3] Hodges PW, Richardson CA. Feedforward contraction of transversus abdominis is not influenced by the direction of arm movement. Exp Brain Res. 1997; 114: 362-370.

[4] Frank C, Kobesova A, Kolar P. Dynamic neuromuscular stabilization & sports rehabilitation. Int J Sports Phys Ther. 2013; 8: 62-73.

[5] Mackey AH, Walt SE, Stott NS. Deficits in upper-limb task performance in children with hemiplegic cerebral palsy as defined by 3-dimensional kinematics. Arch Phys Med Rehabil. 2006; 87: 207-215.

[6] Grimstone SK, Hodges PW. Impaired postural compensation for respiration in people with recurrent low back pain. Exp Brain Res. 2003; 151: 218-224.
[7] Liebenson C. Rehabilitation of the spine: a practitioner's manual. Baltimore: Lippincott Williams & Wilkins; 2007.
[8] Kobesova A, Kolar P, Mlckova J, Svehlik M, Morris CE, Frank C, et al. Effect of functional stabilization training on balance and motor patterns in a patient with Charcot-Marie-Tooth disease. Neuro Endocrinol Lett. 2012; 33: 3-10.
[9] Hodges PW, Richardson CA. Inefficient muscular stabilization of the lumbar spine associated with low back pain. A motor control evaluation of transversus abdominis. Spine. 1996; 21: 2640-2650.
[10] Haruyama K, Kawakami M, Otsuka T. Effect of core stability training on trunk function, standing balance, and mobility in stroke patients. Neurorehabil Neural Repair. 2017; 31(3): 240-249.
[11] Yoon HS, You SH. Reflex-mediated dynamic neuromuscular stabilization in stroke patients: EMG processing and ultrasound imaging. Technol Health Care. 2017; 25(S1): 99-106.
[12] Moseley GL. Widespread brain activity during an abdominal task markedly reduced after pain physiology education: fMRI evaluation of a single patient with chronic low back pain. Aust J Physiother. 2005; 51: 49-52.
[13] Richardson C, Hodges PW, Hides J. Therapeutic exercise for lumbopelvic stabilization: a motor control approach for the treatment and prevention of low back pain: Churchill Livingstone; 2004.
[14] McMeeken J, Beith I, Newham D, Milligan P, Critchley D. The relationship between EMG and change in thickness of transversus abdominis. Clin Biomech (Bristol, Avon). 2004; 19: 337-342.
[15] Whittaker JL. Ultrasound imaging of the lateral abdominal wall muscles in individuals with lumbopelvic pain and signs of concurrent hypocapnia. Man Ther. 2008; 13: 404-410.
[16] Page P, Frank C, Lardner R. Assessment and treatment of muscle imbalance: the Janda approach: Human Kinetics; 2010.
[17] Harel N, Lee SP, Nagaoka T, Kim DS, Kim SG. Origin of negative blood oxygenation level – dependent fMRI signals. J Cereb Blood Flow Metab. 2002; 22: 908-917.
[18] Ridgway GR, Henley SM, Rohrer JD, Scahill RI, Warren JD, Fox NC. Ten simple rules for reporting voxel-based morphometry studies. Neuroimage. 2008; 40: 1429-1435.
[19] Hadland KA, Rushworth MF, Gaffan D, Passingham RE. The effect of cingulate lesions on social behaviour and emotion. Neuropsychologia. 2003; 41: 919-931.
[20] Fontes EB, Okano AH, De Guio F, Schabort EJ, Min LL, Basset FA, Stein DJ, Noakes TD. Brain activity and perceived exertion during cycling exercise: an fMRI study. Br J Sports Med. 2015; 49: 556-560.
[21] Mehta JP, Verber MD, Wieser JA, Schmit BD, Schindler-Ivens SM. A novel technique for examining human brain activity associated with pedaling using fMRI. J Neurosci Methods. 2009; 179: 230-239.
[22] Sidhu SK, Hoffman BW, Cresswell AG, Carroll TJ. Corticospinal contributions to lower limb muscle activity during cycling in humans. J Neurophysiol. 2012; 107: 306-314.
[23] Pelzer EA, Melzer C, Timmermann L, von Cramon DY, Tittgemeyer M. Basal ganglia and cerebellar interconnectivity within the human thalamus. Brain Struct Funct. 2017; 222: 381-392.
[24] Van Dijk KR, Sabuncu MR, Buckner RL. The influence of head motion on intrinsic functional connectivity MRI. Neuroimage. 2012; 59: 431-438.