

# THE LUMBOPELVIC COMPLEX: ADVANCES IN EVALUATION AND TREATMENT

Acute, Subacute, and Recurrent Low Back Pain  
with Movement Coordination Impairments

Independent Study Course 28.3.2

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CONTINUING PHYSICAL THERAPY EDUCATION

ORTHOPAEDIC  
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## REFERENCES

1. Delitto A. Research in low back pain: time to stop seeking the elusive “magic bullet”. *Phys Ther.* 2005;85(3):206-208.
2. Brennan GP, Fritz JM, Hunter SJ, Thackeray A, Delitto A, Erhard RE. Identifying subgroups of patients with acute/subacute “nonspecific” low back pain: results of a randomized clinical trial. *Spine (Phila Pa 1976).* 2006;31(6):623-631.
3. Fritz JM, Cleland JA, Childs JD. Subgrouping patients with low back pain: evolution of a classification approach to physical therapy. *J Orthop Sports Phys Ther.* 2007;37(6):290-302.
4. Stanton TR, Fritz JM, Hancock MJ, et al. Evaluation of a treatment-based classification algorithm for low back pain: a cross-sectional study. *Phys Ther.* 2011;91(4):496-509. doi: 10.2522/ptj.20100272. Epub 2011 Feb 17.
5. Alrwaily M, Timko M, Schneider M, et al. Treatment-based classification system for low back pain: revision and update. *Phys Ther.* 2016;96(7):1057-1066. doi: 10.2522/ptj.20150345. Epub 2015 Dec 4.
6. Delitto A, George SZ, Van Dillen LR, et al. Low back pain. *J Orthop Sports Phys Ther.* 2012;42(4):A1-57. doi: 10.2519/jospt.2012.0301. Epub 2012 Mar 30.
7. Cholewicki J, McGill SM. Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain. *Clin Biomech (Bristol, Avon).* 1996;11(1):1-15.

8. Cholewicki J, Panjabi MM, Khachatryan A. Stabilizing function of trunk flexor-extensor muscles around a neutral spine posture. *Spine (Phila Pa 1976)*. 1997;22(19):2207-2212.
9. McGill SM, Grenier S, Kavcic N, Cholewicki J. Coordination of muscle activity to assure stability of the lumbar spine. *J Electromyogr Kinesiol*. 2003;13(4):353-359.
10. Panjabi MM. A hypothesis of chronic low back pain: ligament subfailure in injuries lead to muscle control dysfunction. *Eur Spine J*. 2006;15(5):668-676. Epub 2005 Jul 27.
11. Panjabi MM. Clinical spinal instability and low back pain. *J Electromyogr Kinesiol*. 2003;13(4):371-379.
12. Panjabi MM. The stabilizing system of the spine. Part I. Function, dysfunction, adaptation, and enhancement. *J Spinal Disord*. 1992;5(4):383-389; discussion 397.
13. Fritz JM, Erhard RE, Hagen BF. Segmental instability of the lumbar spine. *Phys Ther*. 1998;78(8):889-896.
14. Fritz JM, Delitto A, Erhard RE. Comparison of classification-based physical therapy with therapy based on clinical practice guidelines for patients with acute low back pain: a randomized clinical trial. *Spine (Phila Pa 1976)*. 2003;28(13):1363-1371; discussion 1372.
15. Hicks GE, Fritz JM, Delitto A, McGill SM. Preliminary development of a clinical prediction rule for determining which patients with low back pain will respond to a stabilization exercise program. *Arch Phys Med Rehabil*. 2005;86(9):1753-1762.
16. Hodges PW, Richardson CA. Inefficient muscular stabilization of the lumbar spine associated with low back pain. A motor control evaluation of transversus abdominis. *Spine (Phila Pa 1976)*. 1996;21(22):2640-2650.
17. Hodges PW, Richardson CA. Contraction of the abdominal muscles associated with movement of the lower limb. *Phys Ther*. 1997;77(2):132-142; discussion 142-144.
18. O'Sullivan PB. Lumbar segmental 'instability': clinical presentation and specific stabilizing exercise management. *Man Ther*. 2000;5(1):2-12.
19. Cholewicki J, Juluru K, McGill SM. Intra-abdominal pressure mechanism for stabilizing the lumbar spine. *J Biomech*. 1999;32(1):13-17.
20. McGill S. *Low Back Disorders. Evidence-based Prevention and Rehabilitation*. Champaign, IL: Human Kinetics; 2002.
21. Kavcic N, Grenier S, McGill SM. Quantifying tissue loads and spine stability while performing commonly prescribed low back stabilization exercises. *Spine (Phila Pa 1976)*. 2004;29(20):2319-2329.
22. O'Sullivan PB, Phytly GD, Twomey LT, Allison GT. Evaluation of specific stabilizing exercise in the treatment of chronic low back pain with radiologic diagnosis of spondylolysis or spondylolisthesis. *Spine (Phila Pa 1976)*. 1997;22(24):2959-2967.
23. Rabin A, Shashua A, Pizem K, Dickstein R, Dar G. A clinical prediction rule to identify patients with low back pain who are likely to experience short-term success following lumbar stabilization exercises: a randomized controlled validation study. *J Orthop Sports Phys Ther*. 2014;44(1):6-B13. doi: 10.2519/jospt.2014.4888. Epub 2013 Nov 21.
24. Bergmark A. Stability of the lumbar spine. A study in mechanical engineering. *Acta Orthop Scand Suppl*. 1989;230:1-54.
25. Sangwan S, Green RA, Taylor NF. Characteristics of stabilizer muscles: a systematic review. *Physiother Can*. 2014;66(4):348-358. doi: 10.3138/ptc.2013-51.
26. Hodges PW, Richardson CA. Delayed postural contraction of transversus abdominis in low back pain associated with movement of the lower limb. *J Spinal Disord*. 1998;11(1):46-56.
27. Hodges PW, Richardson CA. Altered trunk muscle recruitment in people with low back pain with upper limb movement at different speeds. *Arch Phys Med Rehabil*. 1999;80(9):1005-1012.
28. Hides J, Gilmore C, Stanton W, Bohlscheid E. Multifidus size and symmetry among chronic LBP and healthy asymptomatic subjects. *Man Ther*. 2008;13(1):43-49. Epub 2006 Oct 27.
29. Stokes M, Hides J, Elliott J, Kiesel K, Hodges P. Rehabilitative ultrasound imaging of the posterior paraspinal muscles. *J Orthop Sports Phys Ther*. 2007;37(10):581-595.
30. Hides JA, Richardson CA, Jull GA. Multifidus muscle recovery is not automatic after resolution of acute, first-episode low back pain. *Spine (Phila Pa 1976)*. 1996;21(23):2763-2769.
31. Hides JA, Stokes MJ, Saide M, Jull GA, Cooper DH. Evidence of lumbar multifidus muscle wasting ipsilateral to symptoms in patients with acute/subacute low back pain. *Spine (Phila Pa 1976)*. 1994;19(2):165-172.
32. Stevens VK, Vleeming A, Bouche KG, Mahieu NN, Vanderstraeten GG, Danneels LA. Electromyographic activity of trunk and hip muscles during stabilization exercises in four-point kneeling in healthy volunteers. *Eur Spine J*. 2007;16(5):711-718.
33. Vleeming A, Pool-Goudzwaard AL, Stoeckart R, van Wingerden JP, Snijders CJ. The posterior layer of the thoracolumbar fascia. Its function in load transfer from spine to legs. *Spine (Phila Pa 1976)*. 1995;20(7):753-758.
34. Brown SH, Vera-Garcia FJ, McGill SM. Effects of abdominal muscle coactivation on the externally preloaded trunk: variations in motor control and its effect on spine stability. *Spine (Phila Pa 1976)*. 2006;31(13):E387-393.

35. Wilke HJ, Wolf S, Claes LE, Arand M, Wiesend A. Stability increase of the lumbar spine with different muscle groups. A biomechanical in vitro study. *Spine (Phila Pa 1976)*. 1995;20(2):192-198.
36. Herzog W. The role of titin in eccentric muscle contraction. *J Exp Biol*. 2014;217(Pt 16):2825-2833. doi: 10.1242/jeb.099127.
37. Ward SR, Tomiya A, Regev GJ, et al. Passive mechanical properties of the lumbar multifidus muscle support its role as a stabilizer. *J Biomech*. 2009;42(10):1384-1389. doi: 10.1016/j.jbiomech.2008.09.042. Epub 2009 May 19.
38. Ward SR, Kim CW, Eng CM, et al. Architectural analysis and intraoperative measurements demonstrate the unique design of the multifidus muscle for lumbar spine stability. *J Bone Joint Surg Am*. 2009;91(1):176-185. doi: 10.2106/JBJS.G.01311.
39. Harriss AB, Brown SH. Effects of changes in muscle activation level and spine and hip posture on erector spinae fiber orientation. *Muscle Nerve*. 2015;51(3):426-433. doi: 10.1002/mus.24309. Epub 2015 Jan 5.
40. McGill SM, Hughson RL, Parks K. Changes in lumbar lordosis modify the role of the extensor muscles. *Clin Biomech (Bristol, Avon)*. 2000;15(10):777-780.
41. D'hooge R, Cagnie B, Crombez G, Vanderstraeten G, Dolphens M, Danneels L. Increased intramuscular fatty infiltration without differences in lumbar muscle cross-sectional area during remission of unilateral recurrent low back pain. *Man Ther*. 2012;17(6):584-588. doi: 10.1016/j.math.2012.06.007. Epub 2012 Jul 10.
42. Kjaer P, Bendix T, Sorensen JS, Korsholm L, Leboeuf-Yde C. Are MRI-defined fat infiltrations in the multifidus muscles associated with low back pain? *BMC Med*. 2007;5:2.
43. Fortin M, Macedo LG. Multifidus and paraspinal muscle group cross-sectional areas of patients with low back pain and control patients: a systematic review with a focus on blinding. *Phys Ther*. 2013;93(7):873-888. doi: 10.2522/ptj.20120457. Epub 2013 Mar 15.
44. Hides JA, Stanton WR, McMahon S, Sims K, Richardson CA. Effect of stabilization training on multifidus muscle cross-sectional area among young elite cricketers with low back pain. *J Orthop Sports Phys Ther*. 2008;38(3):101-108. doi: 10.2519/jospt.2008.2658. Epub 2007 Dec 7.
45. Richardson C, Hodges PW, Hides JA. *Therapeutic Exercise for Lumbopelvic Stabilization: A Motor Control Approach for the Treatment and Prevention of Low Back Pain*. 2nd ed. London, UK: Churchill Livingstone; 2004.
46. D'hooge R, Cagnie B, Crombez G, Vanderstraeten G, Achten E, Danneels L. Lumbar muscle dysfunction during remission of unilateral recurrent nonspecific low-back pain: evaluation with muscle functional MRI. *Clin J Pain*. 2013;29(3):187-194. doi: 10.1097/AJP.0b013e31824ed170.
47. Hides JA, Jull GA, Richardson CA. Long-term effects of specific stabilizing exercises for first-episode low back pain. *Spine (Phila Pa 1976)*. 2001;26(11):E243-248.
48. Hebert JJ, Koppenhaver SL, Magel JS, Fritz JM. The relationship of transversus abdominis and lumbar multifidus activation and prognostic factors for clinical success with a stabilization exercise program: a cross-sectional study. *Arch Phys Med Rehabil*. 2010;91(1):78-85. doi: 10.1016/j.apmr.2009.08.146.
49. Zielinski KA, Henry SM, Ouellette-Morton RH, DeSarno MJ. Lumbar multifidus muscle thickness does not predict patients with low back pain who improve with trunk stabilization exercises. *Arch Phys Med Rehabil*. 2013;94(6):1132-1138. doi: 10.1016/j.apmr.2012.12.001. Epub 2012 Dec 7.
50. Hodges PW, Eriksson AE, Shirley D, Gandevia SC. Intra-abdominal pressure increases stiffness of the lumbar spine. *J Biomech*. 2005;38(9):1873-1880.
51. Stanton T, Kawchuk G. The effect of abdominal stabilization contractions on posteroanterior spinal stiffness. *Spine (Phila Pa 1976)*. 2008;33(6):694-701. doi: 10.1097/BRS.0b013e318166e034.
52. Hodges P, Cresswell A, Thorstensson A. Preparatory trunk motion accompanies rapid upper limb movement. *Exp Brain Res*. 1999;124(1):69-79.
53. Gubler D, Mannion AF, Schenk P, et al. Ultrasound tissue Doppler imaging reveals no delay in abdominal muscle feed-forward activity during rapid arm movements in patients with chronic low back pain. *Spine (Phila Pa 1976)*. 2010;35(16):1506-1513. doi: 10.1097/BRS.0b013e3181c3ed41.
54. Mannion AF, Pulkovski N, Schenk P, et al. A new method for the noninvasive determination of abdominal muscle feedforward activity based on tissue velocity information from tissue Doppler imaging. *J Appl Physiol (1985)*. 2008;104(4):1192-1201. doi: 10.1152/jappphysiol.00794.2007. Epub 2008 Jan 10.
55. Mehta R, Cannella M, Henry SM, Smith S, Giszter S, Silfies SP. Trunk postural muscle timing is not compromised in low back pain patients clinically diagnosed with movement coordination impairments. *Motor Control*. 2017;21(2):133-157. doi: 10.1123/mc.2015-0049. Epub 2016 Aug 19.
56. Tsao H, Galea MP, Hodges PW. Driving plasticity in the motor cortex in recurrent low back pain. *Eur J Pain*. 2010;14(8):832-839. doi: 10.1016/j.ejpain.2010.01.001. Epub 2010 Feb 23.
57. Hall L, Tsao H, MacDonald D, Coppieters M, Hodges PW. Immediate effects of co-contraction training on motor control of the trunk muscles in people with recurrent low back pain. *J Electromyogr Kinesiol*. 2009;19(5):763-773. Epub 2007 Nov 26.

58. Tsao H, Hodges PW. Persistence of improvements in postural strategies following motor control training in people with recurrent low back pain. *J Electromyogr Kinesiol.* 2008;18(4):559-567. Epub 2007 Mar 2.
59. Tsao H, Galea MP, Hodges PW. Reorganization of the motor cortex is associated with postural control deficits in recurrent low back pain. *Brain.* 2008;131(Pt 8):2161-2171. doi: 10.1093/brain/awn154. Epub 2008 Jul 18.
60. Hu H, Meijer OG, van Dieen JH, et al. Is the psoas a hip flexor in the active straight leg raise? *Eur Spine J.* 2011;20(5):759-765. doi: 10.1007/s00586-010-1508-5. Epub 2010 Jul 13.
61. Arbanas J, Klasan GS, Nikolic M, Jerkovic R, Miljanovic I, Malnar D. Fibre type composition of the human psoas major muscle with regard to the level of its origin. *J Anat.* 2009;215(6):636-641. doi: 10.1111/j.1469-7580.2009.01155.x.
62. Santaguida PL, McGill SM. The psoas major muscle: a three-dimensional geometric study. *J Biomech.* 1995;28(3):339-345.
63. Dickx N, Cagnie B, Parlevliet T, Lavens A, Danneels L. The effect of unilateral muscle pain on recruitment of the lumbar multifidus during automatic contraction. An experimental pain study. *Man Ther.* 2010;15(4):364-369. doi: 10.1016/j.math.2010.02.002. Epub 2010 Mar 5.
64. Dickx N, Cagnie B, Achten E, et al. Changes in lumbar muscle activity because of induced muscle pain evaluated by muscle functional magnetic resonance imaging. *Spine (Phila PA 1976).* 2008;33(26):E983-989. doi: 10.1097/BRS.0b013e31818917d0.
65. Hodges PW, Tucker K. Moving differently in pain: a new theory to explain the adaptation to pain. *Pain.* 2011;152(3 Suppl):S90-98. doi: 10.1097/BRS.0b013e31818917d0.
66. Hodges PW, Moseley GL, Gabriellson A, Gandevia SC. Experimental muscle pain changes feedforward postural responses of the trunk muscles. *Exp Brain Res.* 2003;151(2):262-271.
67. Hodges PW, Coppieters MW, MacDonald D, Cholewicki J. New insight into motor adaptation to pain revealed by a combination of modelling and empirical approaches. *Eur J Pain.* 2013;17(8):1138-1146. doi: 10.1002/j.1532-2149.2013.00286.x. Epub 2013 Jan 25.
68. Bogduk N, Wilson AS, Tynan W. The human lumbar dorsal rami. *J Anat.* 1982;134(Pt 2):383-397.
69. Bogduk N. The innervation of the lumbar spine. *Spine (Phila Pa 1976).* 1983;8(3):286-293.
70. McLain RF, Pickar JG. Mechanoreceptor endings in human thoracic and lumbar facet joints. *Spine (Phila Pa 1976).* 1998;23(2):168-173.
71. Solomonow M. Sensory-motor control of ligaments and associated neuromuscular disorders. *J Electromyogr Kinesiol.* 2006;16(6):549-567.
72. Holm S, Indahl A, Solomonow M. Sensorimotor control of the spine. *J Electromyogr Kinesiol.* 2002;12(3):219-234.
73. Solomonow M, Zhou BH, Harris M, Lu Y, Baratta RV. The ligamento-muscular stabilizing system of the spine. *Spine (Phila Pa 1976).* 1998;23(23):2552-2562.
74. Kistemaker DA, Van Soest AJK, Wong JD, Kurtzer I, Gribble PL. Control of position and movement is simplified by combined muscle spindle and Golgi tendon organ feedback. *J Neurophysiol.* 2013;109(4):1126-1139. doi: 10.1152/jn.00751.2012. Epub 2012 Oct 24.
75. Dimitriou M, Edin BB. Human muscle spindles act as forward sensory models. *Curr Biol.* 2010;20(19):1763-1767. doi: 10.1016/j.cub.2010.08.049. Epub 2010 Sep 16.
76. Macintosh JE, Valencia F, Bogduk N, Munro RR. The morphology of the human lumbar multifidus. *Clin Biomech (Bristol, Avon).* 1986;1(4):196-204. doi: 10.1016/0268-0033(86)90146-4.
77. Macintosh JE, Bogduk N. The biomechanics of the lumbar multifidus. *Clin Biomech (Bristol, Avon).* 1986;1(4):205-213. doi: 10.1016/0268-0033(86)90147-6.
78. Sung W, Abraham M, Plastaras C, Silfies SP. Trunk motor control deficits in acute and subacute low back pain are not associated with pain or fear of movement. *Spine J.* 2015;15(8):1772-1782. doi: 10.1016/j.spinee.2015.04.010. Epub 2015 Apr 8.
79. Schmid M, Bottaro A, Sozzi S, Schieppati M. Adaptation to continuous perturbation of balance: progressive reduction of postural muscle activity with invariant or increasing oscillations of the center of mass depending on perturbation frequency and vision conditions. *Hum Mov Sci.* 2011;30(2):262-278. doi: 10.1016/j.humov.2011.02.002. Epub 2011 Mar 25.
80. Mok NW, Brauer SG, Hodges PW. Changes in lumbar movement in people with low back pain are related to compromised balance. *Spine (Phila Pa 1976).* 2011;36(1):E45-E52. doi: 10.1097/BRS.0b013e3181dfce83.
81. Newcomer KL, Laskowski ER, Yu B, Johnson JC, An KN. Differences in repositioning error among patients with low back pain compared with control subjects. *Spine (Phila Pa 1976).* 2000;25(19):2488-2493.
82. Newcomer K, Laskowski ER, Yu B, Larson DR, An KN. Repositioning error in low back pain. Comparing trunk repositioning error in subjects with chronic low back pain and control subjects. *Spine (Phila Pa 1976).* 2000;25(2):245-250.
83. Claeys K, Brumagne S, Dankaerts W, Kiers H, Janssens L. Decreased variability in postural control strategies in young people with non-specific low back pain is associated with altered proprioceptive reweighting. *Eur*

- J Appl Physiol.* 2011;111(1):115-123. doi: 10.1007/s00421-010-1637-x. Epub 2010 Sep 8.
84. Brumagne S, Cordo P, Verschueren S. Proprioceptive weighting changes in persons with low back pain and elderly persons during upright standing. *Neurosci Lett.* 2004;366(1):63-66.
  85. Brumagne S, Cordo P, Lysens R, Verschueren S, Swinnen S. The role of paraspinal muscle spindles in lumbosacral position sense in individuals with and without low back pain. *Spine (Phila Pa 1976).* 2000;25(8):989-994.
  86. Brumagne S, Lysens R, Swinnen S, Verschueren S. Effect of paraspinal muscle vibration on position sense of the lumbosacral spine. *Spine (Phila Pa 1976).* 1999;24(13):1328-1331.
  87. Escamilla RF, Lewis C, Bell D, et al. Core muscle activation during Swiss ball and traditional abdominal exercises. *J Orthop Sports Phys Ther.* 2010;40(5):265-276. doi: 10.2519/jospt.2010.3073.
  88. Pelletier R, Higgins J, Bourbonnais D. Is neuroplasticity in the central nervous system the missing link to our understanding of chronic musculoskeletal disorders? *BMC Musculoskelet Disord.* 2015;16:25. doi: 10.1186/s12891-015-0480-y.
  89. Tsao H, Danneels LA, Hodges PW. ISSLS prize winner: Smudging the motor brain in young adults with recurrent low back pain. *Spine (Phila Pa 1976).* 2011;36(21):1721-1727. doi: 10.1097/BRS.0b013e31821c4267.
  90. Schabrun SM, Elgueta-Cancino EL, Hodges PW. Smudging of the motor cortex is related to the severity of low back pain. *Spine (Phila Pa 1976).* 2017;42(15):1172-1178. doi: 10.1097/BRS.0000000000000938.
  91. Lloyd D, Findlay G, Roberts N, Nurmikko T. Differences in low back pain behavior are reflected in the cerebral response to tactile stimulation of the lower back. *Spine (Phila Pa 1976).* 2008;33(12):1372-1377. doi: 10.1097/BRS.0b013e3181734a8a.
  92. Flor H, Braun C, Elbert T, Birbaumer N. Extensive reorganization of primary somatosensory cortex in chronic back pain patients. *Neurosci Lett.* 1997;224(1):5-8.
  93. Hodges PW. Pain and motor control: from the laboratory to rehabilitation. *J Electromyogr Kinesiol.* 2011;21(2):220-228. doi: 10.1016/j.jelekin.2011.01.002.
  94. Brumagne S, Janssens L, Knapen S, Claeys K, Suuden-Johanson E. Persons with recurrent low back pain exhibit a rigid postural control strategy. *Eur Spine J.* 2008;17(9):1177-1184. doi: 10.1007/s00586-008-0709-7. Epub 2008 Jul 2.
  95. O'Sullivan P. Diagnosis and classification of chronic low back pain disorders: maladaptive movement and motor control impairments as underlying mechanism. *Man Ther.* 2005;10(4):242-255.
  96. O'Sullivan P. It's time for change with the management of non-specific chronic low back pain. *Br J Sports Med.* 2012;46(4):224-227. doi: 10.1136/bjsm.2010.081638. Epub 2011 Aug 4.
  97. Boudreau SA, Farina D, Falla D. The role of motor learning and neuroplasticity in designing rehabilitation approaches for musculoskeletal pain disorders. *Man Ther.* 2010;15(5):410-414. doi: 10.1016/j.math.2010.05.008. Epub 2010 Jul 7.
  98. Tsao H, Druitt TR, Schollum TM, Hodges PW. Motor training of the lumbar paraspinal muscles induces immediate changes in motor coordination in patients with recurrent low back pain. *J Pain.* 2010;11(11):1120-1128. doi: 10.1016/j.jpain.2010.02.004.
  99. Tsao H, Hodges PW. Persistence of improvements in postural strategies following motor control training in people with recurrent low back pain. *J Electromyogr Kinesiol.* 2008;18(4):559-567.
  100. Massé-Alarie H, Beaulieu LD, Preuss R, Schneider C. Influence of paravertebral muscles training on brain plasticity and postural control in chronic low back pain. *Scand J Pain.* 2016;12:74-83. doi: 10.1016/j.sjpain.2016.03.005. Epub 2016 May 11.
  101. Jensen JL, Marstrand PC, Nielsen JB. Motor skill training and strength training are associated with different plastic changes in the central nervous system. *J Appl Physiol (1985).* 2005;99(4):1558-1568.
  102. Adkins DL, Boychuk J, Remple MS, Kleim JA. Motor training induces experience-specific patterns of plasticity across motor cortex and spinal cord. *J Appl Physiol (1985).* 2006;101(6):1776-1782.
  103. Panjabi MM. The stabilizing system of the spine. Part II. Neutral zone and instability hypothesis. *J Spinal Disord.* 1992;5(4):390-396; discussion 397.
  104. MacDonald D, Moseley GL, Hodges PW. Why do some patients keep hurting their back? Evidence of ongoing back muscle dysfunction during remission from recurrent back pain. *Pain.* 2009;142(3):183-188. doi: 10.1016/j.pain.2008.12.002. Epub 2009 Jan 30.
  105. Pool-Goudzwaard A. Merger of models on clinical instability – misleading for patients and clinicians? *Man Ther.* 2016;21:1. doi: 10.1016/S1356-689X(15)00235-0.
  106. Laslett M, Oberg B, Aprill CN, McDonald B. Centralization as a predictor of provocation discography results in chronic low back pain, and the influence of disability and distress on diagnostic power. *Spine J.* 2005;5(4):370-380.
  107. Stanton TR, Latimer J, Maher CG, Hancock MJ. How do we define the condition 'recurrent low back pain'? A systematic review. *Eur Spine J.* 2010;19(4):533-539. doi: 10.1007/s00586-009-1214-3. Epub 2009 Nov 18.

108. Main CJ, George SZ. Psychologically informed practice for management of low back pain: future directions in practice and research. *Phys Ther.* 2011;91(5):820-824. doi: 10.2522/ptj.20110060. Epub 2011 Mar 30.
109. Linton SJ, Shaw WS. Impact of psychological factors in the experience of pain. *Phys Ther.* 2011;91(5):700-711. doi: 10.2522/ptj.20100330. Epub 2011 Mar 30.
110. Feuerstein M, Beattie P. Biobehavioral factors affecting pain and disability in low back pain: mechanisms and assessment. *Phys Ther.* 1995;75(4):267-280.
111. Boersma K, Linton SJ. Screening to identify patients at risk: profiles of psychological risk factors for early intervention. *Clin J Pain.* 2005;21(1):38-43; discussion 69-72.
112. Vlaeyen JW, Linton SJ. Fear-avoidance and its consequences in chronic musculoskeletal pain: a state of the art. *Pain.* 2000;85(3):317-332.
113. Beneciuk JM, Bishop MD, Fritz JM, et al. The STarT back screening tool and individual psychological measures: evaluation of prognostic capabilities for low back pain clinical outcomes in outpatient physical therapy settings. *Phys Ther.* 2013;93(3):321-333. doi: 10.2522/ptj.20120207. Epub 2012 Nov 2.
114. Beneciuk JM, Robinson ME, George SZ. Low back pain subgroups using fear-avoidance model measures results of a cluster analysis. *Clin J Pain.* 2012;28(8):658-666. doi: 10.1097/AJP.0b013e31824306ed.
115. Overmeer T, Boersma K, Denison E, Linton SJ. Does teaching physical therapists to deliver a biopsychosocial treatment program result in better patient outcomes? A randomized controlled trial. *Phys Ther.* 2011;91(5):804-819. doi: 10.2522/ptj.20100079. Epub 2011 Mar 30.
116. Shaw WS, Pransky G, Roter DL, Winters T, Tveito TH, Larson SM. The effects of patient-provider communication on 3-month recovery from acute low back pain. *J Am Board Fam Med.* 2011;24(1):16-25. doi: 10.3122/jabfm.2011.01.100054.
117. Vlaeyen JW, Seelen HA, Peters M, et al. Fear of movement/(re)injury and muscular reactivity in chronic low back pain patients: an experimental investigation. *Pain.* 1999;82(3):297-304.
118. Macedo LG, Maher CG, Hancock MJ, et al. Predicting response to motor control exercises and graded activity for low back pain patients: preplanned secondary analysis of a randomized controlled trial. *Phys Ther.* 2014;94(11):1543-1554. doi: 10.2522/ptj.20140014. Epub 2014 Jul 10.
119. Costa LO, Maher CG, Latimer J, et al. Motor control exercise for chronic low back pain: a randomized placebo-controlled trial. *Phys Ther.* 2009;89(12):1275-1286. doi: 10.2522/ptj.20090218. Epub 2009 Nov 5.
120. Steele J, Bruce-Low S, Smith D. A review of the specificity of exercises designed for conditioning the lumbar extensors. *Br J Sports Med.* 2015;49(5):291-297. doi: 10.1136/bjsports-2013-092197. Epub 2013 Oct 3.
121. Unsgaard-Tøndel M, Fladmark AM, Salvesen Ø, Vasseljen O. Motor control exercises, sling exercises, and general exercises for patients with chronic low back pain: a randomized controlled trial with 1-year follow-up. *Phys Ther.* 2010;90(10):1426-1440. doi: 10.2522/ptj.20090421. Epub 2010 Jul 29.
122. Henry SM, Van Dillen LR, Ouellette-Morton RH, et al. Outcomes are not different for patient-matched versus nonmatched treatment in subjects with chronic recurrent low back pain: a randomized clinical trial. *Spine J.* 2014;14(12):2799-2810. doi: 10.1016/j.spinee.2014.03.024. Epub 2014 Mar 22.
123. Macedo LG, Maher CG, Latimer J, McAuley JH. Motor control exercise for persistent, nonspecific low back pain: a systematic review. *Phys Ther.* 2009;89(1):9-25. doi: 10.2522/ptj.20080103. Epub 2008 Dec 4.
124. Macedo LG, Latimer J, Maher CG, et al. Motor control or graded activity exercises for chronic low back pain? A randomised controlled trial. *BMC Musculoskelet Disord.* 2008;9:65. doi: 10.1186/1471-2474-9-65.
125. Macedo LG, Latimer J, Maher CG, et al. Effect of motor control exercises versus graded activity in patients with chronic nonspecific low back pain: a randomized controlled trial. *Phys Ther.* 2012;92(3):363-377. doi: 10.2522/ptj.20110290. Epub 2011 Dec 1.
126. van Middelkoop M, Rubinstein S, Kuijpers T, et al. A systematic review on the effectiveness of physical and rehabilitation interventions for chronic non-specific low back pain. *Eur Spine J.* 2011;20(1):19-39. doi: 10.1007/s00586-010-1518-3. Epub 2010 Jul 18.
127. Koumantakis GA, Watson PJ, Oldham JA. Supplementation of general endurance exercise with stabilisation training versus general exercise only: physiological and functional outcomes of a randomised controlled trial of patients with recurrent low back pain. *Clin Biomech (Bristol, Avon).* 2005;20(5):474-482.
128. Koumantakis GA, Watson PJ, Oldham JA. Trunk muscle stabilization training plus general exercise versus general exercise only: randomized controlled trial of patients with recurrent low back pain. *Phys Ther.* 2005;85(3):209-225.
129. van Tulder M, Malmivaara A, Esmail R, Koes B. Exercise therapy for low back pain: a systematic review within the framework of the cochrane collaboration back review group. *Spine (Phila Pa 1976).* 2000;25(21):2784-2796.
130. Cairns MC, Foster NE, Wright C. Randomized controlled trial of specific spinal stabilization exercises and conventional physiotherapy for recurrent low back pain. *Spine (Phila Pa 1976).* 2006;31(19):E670-681.
131. Dankaerts W, O'Sullivan P, Burnett A, Straker L, Davey P, Gupta R. Discriminating healthy controls

- and two clinical subgroups of nonspecific chronic low back pain patients using trunk muscle activation and lumbosacral kinematics of postures and movements: a statistical classification model. *Spine (Phila Pa 1976)*. 2009;34(15):1610-1618. doi: 10.1097/BRS.0b013e3181aa6175.
132. Van Damme B, Stevens V, Perneel C, et al. A surface electromyography based objective method to identify patients with nonspecific chronic low back pain, presenting a flexion related movement control impairment. *J Electromyogr Kinesiol*. 2014;24(6):954-964. doi: 10.1016/j.jelekin.2014.09.007. Epub 2014 Sep 28.
  133. Fritz JM, Cleland JA, Brennan GP. Does adherence to the guideline recommendation for active treatments improve the quality of care for patients with acute low back pain delivered by physical therapists? *Med Care*. 2007;45(10):973-980.
  134. Sahrman SA. *Diagnosis and Treatment of Movement Impairment Syndromes*. St. Louis, MO: Mosby; 2001.
  135. Biely SA, Silfies SP, Smith SS, Hicks GE. Clinical observation of standing trunk movements: what do the aberrant movement patterns tell us? *J Orthop Sports Phys Ther*. 2014;44(4):262-272. doi: 10.2519/jospt.2014.4988. Epub 2014 Jan 22.
  136. Teyhen DS, Flynn TW, Childs JD, Abraham LD. Arthrokinematics in a subgroup of patients likely to benefit from a lumbar stabilization exercise program. *Phys Ther*. 2007;87(3):313-325.
  137. Semmler JG. Motor unit synchronization and neuromuscular performance. *Exerc Sport Sci Rev*. 2002;30(1):8-14.
  138. Yao W, Fuglevand RJ, Enoka RM. Motor-unit synchronization increases EMG amplitude and decreases force steadiness of simulated contractions. *J Neurophysiol*. 2000;83(1):441-452.
  139. Hicks GE, Fritz JM, Delitto A, Mishock J. Interrater reliability of clinical examination measures for identification of lumbar segmental instability. *Arch Phys Med Rehabil*. 2003;84(12):1858-1864.
  140. Kiesel KB, Uhl TL, Underwood FB, Rodd DW, Nitz AJ. Measurement of lumbar multifidus muscle contraction with rehabilitative ultrasound imaging. *Man Ther*. 2007;12(2):161-166.
  141. Hebert JJ, Koppenhaver SL, Teyhen DS, Walker BF, Fritz JM. The evaluation of lumbar multifidus muscle function via palpation: reliability and validity of a new clinical test. *Spine J*. 2015;15(6):1196-1202. doi: 10.1016/j.spinee.2013.08.056. Epub 2013 Oct 4.
  142. Nelson-Wong E, Flynn T, Callaghan JP. Development of active hip abduction as a screening test for identifying occupational low back pain. *J Orthop Sports Phys Ther*. 2009;39(9):649-657. doi: 10.2519/jospt.2009.3093.
  143. Nelson-Wong E, Callaghan JP. Transient low back pain development during standing predicts future clinical low back pain in previously asymptomatic individuals. *Spine (Phila Pa 1976)*. 2014;39(6):E379-383. doi: 10.1097/BRS.0000000000000191.
  144. Nelson-Wong E, Gallant P, Alexander S, et al. Multiplanar lumbopelvic control in patients with low back pain: is multiplanar assessment better than single plane assessment in discriminating between patients and healthy controls? *J Man Manip Ther*. 2016;24(1):45-50. doi: 10.1179/2042618614Y.0000000078.
  145. Wong TK, Lee RY. Effects of low back pain on the relationship between the movements of the lumbar spine and hip. *Hum Mov Sci*. 2004;23(1):21-34.
  146. Nelson-Wong E, Alex B, Csepe D, Lancaster D, Callaghan JP. Altered muscle recruitment during extension from trunk flexion in low back pain developers. *Clin Biomech (Bristol, Avon)*. 2012;27(10):994-998. doi: 10.1016/j.clinbiomech.2012.07.007. Epub 2012 Aug 9.
  147. Dankaerts W, O'Sullivan PB, Straker LM, Burnett AF, Skouen JS. The inter-examiner reliability of a classification method for non-specific chronic low back pain patients with motor control impairment. *Man Ther*. 2006;11(1):28-39.
  148. Dankaerts W, O'Sullivan P, Burnett A, Straker L. Altered patterns of superficial trunk muscle activation during sitting in nonspecific chronic low back pain patients: importance of subclassification. *Spine (Phila Pa 1976)*. 2006;31(17):2017-2023.
  149. Van Dillen LR, Sahrman SA, Norton BJ, Caldwell CA, McDonnell MK, Bloom NJ. Movement system impairment-based categories for low back pain: stage 1 validation. *J Orthop Sports Phys Ther*. 2003;33(3):126-142.
  150. Dankaerts W, O'Sullivan P. The validity of O'Sullivan's classification system (CS) for a sub-group of NS-CLBP with motor control impairment (MCI): overview of a series of studies and review of the literature. *Man Ther*. 2011;16(1):9-14. doi: 10.1016/j.math.2010.10.006. Epub 2010 Nov 20.
  151. Harris-Hayes M, Van Dillen LR. The inter-tester reliability of physical therapists classifying low back pain problems based on the movement system impairment classification system. *PM R*. 2009;1(2):117-126. doi: 10.1016/j.pmrj.2008.08.001. Epub 2008 Dec 27.
  152. Karayannis NV, Jull GA, Hodges PW. Movement-based subgrouping in low back pain: synergy and divergence in approaches. *Physiotherapy*. 2016;102(2):159-169. doi: 10.1016/j.physio.2015.04.005. Epub 2015 Jun 3.
  153. Van Dillen LR, Sahrman SA, Wagner JM. Classification, intervention, and outcomes for a person with lumbar rotation with flexion syndrome. *Phys Ther*. 2005;85(4):336-351.



154. Aasa B, Berglund L, Michaelson P, Aasa U. Individualized low-load motor control exercises and education versus a high-load lifting exercise and education to improve activity, pain intensity, and physical performance in patients with low back pain: a randomized controlled trial. *J Orthop Sports Phys Ther.* 2015;45(2):77-85, B1-4. doi: 10.2519/jospt.2015.5021.
155. Paris SV. Physical signs of instability. *Spine (Phila Pa 1976).* 1985;10(3):277-279.
156. McKenzie R, May S. *The Lumbar Spine: Mechanical Diagnosis & Therapy.* Vol 1. 2 ed. Minneapolis, MN: Orthopedic Physical Therapy Products; 2003.
157. McKenzie R. Understanding centralisation. *J Orthop Sports Phys Ther.* 1999;29(8):487-489.
158. Skytte L, May S, Petersen P. Centralization: its prognostic value in patients with referred symptoms and sciatica. *Spine (Phila Pa 1976).* 2005;30(11):E293-299.
159. Long A, May S, Fung T. Specific directional exercises for patients with low back pain: a case series. *Physiother Can.* 2008;60(4):307-317. doi: 10.3138/physio.60.4.307. Epub 2008 Nov 12.
160. Kulig K, Beneck GJ, Selkowitz DM, et al. An intensive, progressive exercise program reduces disability and improves functional performance in patients after single-level lumbar microdiscectomy. *Phys Ther.* 2009;89(11):1145-1157. doi: 10.2522/ptj.20080052. Epub 2009 Sep 24.
161. Beneck GJ, Story JW, Donald S. Postural cueing to increase lumbar lordosis increases lumbar multifidus activation during trunk stabilization exercises: electromyographic assessment using intramuscular electrodes. *J Orthop Sports Phys Ther.* 2016;46(4):293-299. doi: 10.2519/jospt.2016.6174. Epub 2016 Mar 8.
162. Chiviacowsky S, Wulf G. Feedback after good trials enhances learning. *Res Q Exerc Sport.* 2007;78(2):40-47.
163. Winstein CJ, Schmidt RA. Reduced frequency of knowledge of results enhances motor skill learning. *J Exp Psychol Learn Mem Cogn.* 1990;16(4):677-691.
164. Blandin Y, Toussaint L, Shea CH. Specificity of practice: interaction between concurrent sensory information and terminal feedback. *J Exp Psychol Learn Mem Cogn.* 2008;34(4):994-1000. doi: 10.1037/0278-7393.34.4.994.
165. Van Dillen LR, Sahrman SA, Norton BJ, et al. Reliability of physical examination items used for classification of patients with low back pain. *Phys Ther.* 1998;78(9):979-988.