*Send Orders for Reprints to reprints@benthamscience.ae*



The Open Sports Sciences Journal

Content list available at: www.benthamopen.com/TOSSJ/

DOI: 10.2174/1875399X01710010114


LETTER

# Lifting Loads on Unstable Platforms - A Supplementary View on Stabilizer Muscles and Terminological Issues

Armin Kibele*

*University of Kassel, Institute for Sports and Sport Science, Kassel, Germany*

Received: January 13, 2017 Revised: April 13, 2017 Accepted: June 07, 2017

**Abstract:** Many open motor skills, for example in team sports and combat sports, are executed under mild to severe conditions of instability. Therefore, over the past two decades, coaching professionals and athletes have shown increasing interest in training routines to enhance the physical prerequisites for strength performance in this regard. Exercise scientists have identified instability resistance training as a possible means to improve strength performance under conditions of instability with a special emphasis on the core muscles. In this letter article, more specifically, we firstly argue that effects of resistance training may be found not only in the core muscles but in the stabilizer muscles in general. Moreover, specific testing procedures are needed to assess strength performance under instability as compared to stable testing. As a second issue of this letter article, we consider instability to be an inappropriate term to characterize mild to moderate equilibrium disturbances during competition and exercise. Instead, when conceptualizing the human body as a dynamic system, metastability appears to better suit the conditions of strength performance on slippery surfaces, waves, during gusts of wind or tackling opponents for example. In fact, this term is conventionally used to characterize other dynamic systems in thermodynamics, financial markets, climatology, and social groups for instance. In the recent past, metastability has been discussed for issues in motor control as well. Hence, we argue that metastability idea should be applied to exercise science as well when assigning the biomechanical equilibrium conditions during perturbed strength performance.

## INTRODUCTION

On many occasions in sports, athletes, when executing motor skills, can experience balance disturbances such as when tackling opponents in team sports and combat sports, cutting maneuvers, slippery turf, strong winds or waves, for example when surfing on a board, or when managing moguls in alpine skiing. During the past two decades, corresponding training methods have evolved and denoted as instability strength or resistance training (IRT) [1 - 5]. Exercises have been suggested to lift loads or perform jumps on unstable platforms such as wobble boards, inflatable rubber discs, or bosu balls [1, 6]. In addition, more recently, muscle activities have been examined during instability lifting exercises with unstable loads (for example: weights suspended from a parallel bar by an elastic band [7] or plastic pipes with liquids [8].

Unfortunately, so far, inconsistent results were provided for any clear superiority of IRT over traditional resistance training [5]. Aside from possible similarities in the physiological adaptations, the reasons for this uncertainty may be related to a lack of specific knowledge on the neuromuscular activation in the primary movers and the stabilizer muscles during instability exercises as well. In addition, a general misconception of the instability notion and a possible mismatch of training and testing procedures may have obscured the clear understanding of existent results. It is the aim of this letter article to forward a supplementary view by analyzing the literature towards specific muscle activation differences in the primary movers and the stabilizers during instability strength exercises. Further, we argue that instability is an inappropriate term to characterize mild to moderate equilibrium disturbances during competition and exercise. A metastability approach to conceptualize human motor behavior during ongoing variations in mechanical equilibrium is forwarded and supplementary conclusions on training and assessment are derived.

* Address correspondence to this author at the Institute for Sports and Sport Science, University of Kassel, Damaschkestrasse 25, D-34121 Kassel, Germany; Tel: + 45 561804 5357; E-mail: akibele@uni-kassel.de

1875-399X/17 2017 Bentham Open

## INSTABILITY STRENGTH EXERCISES

In the past, authors have attributed the benefits of IRT to strengthening of the core [2, 9, 10] as a key factor in athletic performance and injury prevention [6, 11 - 15]. In particular, it has been the core muscles with stabilizing and force transducing functions within kinetic chains, for example during throws and jumps, which have been considered [10, 13]. However, little attention has been paid to the distinction between primary movers and stabilizer muscles in this regard.

From a theoretical view point, strength training effects have been traditionally categorized by either muscle hypertrophy or improved neuromuscular activation [16, 17]. Depending on their line of action in respect to the overall movement direction and on the co-activation of their antagonists, activated muscles may be roughly categorized as stabilizers or primary movers. Whilst, specific results on any muscle hypertrophy effects of IRT in the stabilizers and the primary movers are amiss [5] neural adaptations through IRT appear to be more plausible for both categories.

For example, muscle activation studies for the primary movers (*e.g*., m. pectoralis m. or m. triceps br.) during barbell chest presses on stable versus unstable support platforms showed either no differences (*e.g*., swiss balls vs. bench) [18 - 21] or lower degrees of muscle activation [8, 22, 23]. Similar results were found in the leg extensor muscles (for example: m. quadriceps fem.) during squatting exercises or plyometric jumps on unstable platform supports (*e.g*., wobble boards or inflatable dyna discs). While some researchers found lower muscle activation in the primary movers during unstable exercises [24], others did not find any differences [7, 21, 25, 26]. Reductions in the muscle activation levels for the leg extensors were also reported for vertical jumps and drop jumps on unstable *vs*. stable platform supports [27].

In contrast, stabilizer muscles (*e.g*., m. rectus abdominis, m. obliquus externus abdominis, m. erector spinae, or m. soleus) showed higher activation levels during unstable as compared to stable exercise modes in both barbell chest press exercises [8, 20, 22, 23, 28 - 30] and squatting tasks [7, 21, 24], and for postural balance tasks [31]. Stabilizer muscles are considered to contribute to joint stiffening through co-contractions while showing an early activation onset in response to perturbation using feed-forward and/or feedback control processes [32]. In addition, larger muscle activation levels in the primary movers were also reported for instability exercises with dumbbells as compared to barbell exercises, with the latter less demanding in regards to postural stability [33].

In summary, studies in the literature show a smaller, or at best similar, neuromuscular activation in the primary movers for chest presses and squatting exercises on unstable as compared to stable platforms. The opposite is true for the stabilizer muscles. Here, all in all, larger muscle activities are detected when exercising under unstable vs. stable conditions while it did not matter whether unstable platforms or unstable loads were used [7, 8]. Therefore, IRT appears to provide a better adaptation stimulus for the stabilizer muscles than for the primary movers [34]. In addition, instability exercises appear to be better suited for a weight loss program as the total energy cost was found to be significantly larger when exercising on unstable platforms [35]. Consequently, IRT may be considered as a useful tool to promote stabilizer strength. Furthermore, misconceptions should be eliminated such that IRT is an additional rather than a competing alternative to traditional strength training regimens [19, 20, 36 - 38]. In turn, IRT does not provide a suitable muscle adaptation stimulus for the primary movers. Instead, stable exercise conditions with maximal loads are required to provide changes in the neuromuscular activation pattern of the primary movers [16, 17].

A further point deserves notice. In the past, most studies on instability strength performance have used bench press exercises when lying prone on swiss balls, or squatting exercises on wobble boards or dyna discs, while aiming for a strengthening of the core [see reviews by 1, 2, 5, 39]. Here, primary movers of the trunk and the leg muscles and trunk stabilizers were analyzed. However, studies on the hip stabilizers (for example: adductor and abductor muscles) are hardly known in the literature on IRT. While a tendency for larger muscle activations in the gluteus medius was found for unstable *versus* stable stance conditions [40], it is yet unclear whether and how the hip stabilizer muscles will change their activation pattern from stable to unstable support conditions during leg extension tasks with loads. However, hip stabilizer strength and adductor-to-abductor strength ratio have been identified as suitable indicators for the risk of groin injuries, for example, in soccer players and hockey players [41 - 48]. As a conclusion, it is therefore important to relate IRT not only to the anatomical core [2] but to stabilizer muscles in general.

## A METASTABILITY APPROACH TO HUMAN MOTOR BEHAVIOR

So far, the IRT has been suggested to prepare the athlete for balance disturbances encountered during competition. However, instability may not be an appropriate term to capture ongoing variations in the body equilibrium.

Equilibrium typically describes the state of a body that is not changing its speed or direction when all forces acting on it are completely balanced. Traditionally, three typical states of equilibrium are distinguished by their responsive behavior to perturbations [49]. When in stable equilibrium, systems will return to their original location if displaced. In turn, systems are in a state of unstable equilibrium when they do not return to their original location contingent to even the slightest displacements but instead pass into new states of equilibrium. Objects showing neither tendency to move back or away from their initial states are referred to as in a neutral state of equilibrium.

These conditions of true equilibrium are typical for rigid bodies but rarely found in living bodies. Here, variable muscular activity at rest and during motion, aside from ongoing mechanics of vital processes such as breathing, cardio-vascular functioning, and digestion, constrain true states of equilibrium. Therefore, a stable state of biomechanical equilibrium must be considered a virtual target condition of the mover attempting to control for body posture during ongoing changes of static and dynamic environmental task constraints. Rather, the maintenance or control of a given state of motion is typically achieved in a metastable state of equilibrium when aiming for, but rarely reaching, stable equilibrium.

A metastable state is not a true state of equilibrium but an intermediate to the stable and unstable states. For example, the stock market and its indices is not greatly disturbed by single buys or sales. However, for example, near the end of a positive trend, the participants watching the market may begin to sense that the market is approaching an unstable state of equilibrium. A butterfly effect may arise whereby a few traders sell, pushing the market imperceptibly lower. As a consequence, more traders, sensing this microscopic downturn, may decide to sell. An avalanche of sales may evolve with all traders hoping to protect their profits by selling before the market drops. Such processes have been conceptualized by specific financial market models [50] based on general theories of metastability in non-linear dynamic systems [51].

Dynamic systems, in general, comprise of inherent mechanisms including processes of self-organization and self-organized criticality which compensate for small disturbances to maintain a state of metastability between stable and unstable states of equilibrium. While stable, unstable, and neutral states of equilibrium are traditionally referred to rigid bodies with all acting influences compensated by others, metastable states of equilibrium are typically found in dynamic systems such as in thermodynamics [52], financial markets [53], protein folding [54], climatology [55], fluid physics [56], digital systems [57], electrical circuits [58], neuroscience [59], brain dynamics [60], cognitive functioning [61], and social group dynamics [62].

In the past decade, metastability has already become an issue in human motor coordination to conceptually describe the non-linear dynamics of adaptive behavior in the body when aiming for a state of relative coordination within changing performance environments [63, 64]. This work is closely connected to the understanding of human coordination dynamics [65]. For that purpose, methodological approaches have evolved providing experimental evidence on metastable system dynamics for a punching task in boxing [66], a batting task in cricket [67], in postural dynamics [68], and to capture interrelations in social coordination, tactical solutions and learning [69]. Although these studies have predominantly focused on the coordination transitions between preferred movements while looking for attractor states and transition within the perceptual motor workspace, corresponding approaches can be found for the issue of stability, variability and mechanical equilibrium in human locomotor behavior as well. For example, England and Granata [70] have provided results on the stability and kinematic variability of human gait using the Lyapunov stability model.

In a broader sense, humans are constantly in a state of metastability. When standing erect, they continuously show swaying movements of the center of gravity which are easily being compensated for by predominantly unconscious motor control mechanisms. Here, the movers will perceive their state of motion as stable, while their state of equilibrium is metastable. For large challenges of balance, the movers may perceive their state of motion to be unstable while moving the present state of metastable equilibrium towards unstable states of equilibrium. For example, during athletic training on an instability device (*e.g.*, wobble boards, exercise balls) or during running on uneven surfaces, small to moderate swaying would be compensated for in order to maintain a metastable state of equilibrium. Only large disturbances will force the athlete's center of mass projection to travel to and beyond the boundaries of the base of support such that he will leave the metastable state of equilibrium, approach an unstable equilibrium, and eventually drop from the device.

To maintain the metastable state of equilibrium, a variety of sensory systems may be employed to constantly monitor the metastable state and correct internal and external perturbations through a number of actuators through the neuromuscular system [71]. For example, postural sway, which can be affected by internal perturbations such as changes in thoracic volume with ventilation [72], is counteracted by plantar flexor contractions that can occur on average two to three times per second [73]. Subcortical areas such as the cerebellum, predict and execute the plantar flexor contraction forces necessary to correct these perturbations [74]. For the locomotor system, mechanical models have been established to show the shock absorbing and self-stabilizing qualities in the architecture of muscles, tendons, and ligaments [75]. Therefore, the human body must be conceptualized as a dynamic system with its inherent mechanisms to maintain metastable states of equilibrium. These mechanisms refer to interactions of voluntary control, interconnected neural circuits and reflex loops on one side [76], and mechanical properties encompassing equilibrium point control, and elasticity of muscles, tendon and ligaments on the other side [75]. Metastability would more properly denote the situational constraints of human motor performance in sports as compared to the traditional states of equilibrium with reference to rigid bodies highlighted in traditional textbooks of sport biomechanics and movement science [77, 78].

Unfortunately, in the past, an equivocal use of terms and expressions related to equilibrium, stability, and balance issues in sports has obscured a clear communication of metastability in human motion, not only in scientific discussions but in everyday language as well. To resolve this issue, Kibele and co-workers [79] have suggested a clarification in the proper use of corresponding terms related to human motor performance.

## CONCLUSION

The above outline of the metastability concept to human motor performance has highlighted the specific benefits of IRT to improve stabilizer strength including sensorimotor interaction. However, at this point, it remains unclear whether IRT or specific strength training for the stabilizer muscles under stable conditions should be favored. More research is needed in this respect. According to the principle of exercise-type specificity [80, 81], however, we may speculate that the overall muscle activation pattern in IRT including stabilizers and primary movers to be closer to the goal movement during competition than an isolated strengthening task for the stabilizers only.

Furthermore, metastability should be viewed as a general state in human motor performance rather than an exception of it. For this instance, testing for metastable strength performance might pose a new challenge for performance analysis in sports. So far, biomechanical tests on stable surfaces have been predominantly used to analyze effects of IRT interventions [36]. However, it appears plausible that stable execution conditions are inadequate, as compared to unstable testing, to capture the specific adaptation effects of strength exercises on unstable surfaces. A study by Kibele and Behm [82] showed superior task performance in a test with high demands for locomotor stability (one-legged hopping test) of subjects who previously trained under unstable as compared to stable execution conditions, while stable tests did not provide differences between the groups. Therefore, comparable tests on stable *versus* unstable support bases are needed to examine strength and agility under opposing degrees of metastability. From the above, we hypothesize that benefits of IRT *versus* traditional resistance training regimens will be identified in unstable rather than in stable strength testing conditions. Stabilizer strength might prove to be a yet unattended athletic ability in sports.

## CONFLICT OF INTEREST

The author (editor) declares no conflict of interest, financial or otherwise.

## ACKNOWLEDGEMENTS

Declared none.

## REFERENCES

[1] Behm DG, Anderson KG. The role of instability with resistance training. J Strength Cond Res 2006; 20(3): 716-22.
[PMID: 16937988]

[2] Behm DG, Drinkwater EJ, Willardson JM, Cowley PM. The use of instability to train the core musculature. Appl Physiol Nutr Metab 2010; 35(1): 91-108.
[http://dx.doi.org/10.1139/H09-127] [PMID: 20130672]

[3] Fowles JR. What I always wanted to know about instability training. Appl Physiol Nutr Metab 2010; 35(1): 89-90.
[http://dx.doi.org/10.1139/H09-134] [PMID: 20130671]

[4] Behm DG, Colado JC, Colado JC. Instability resistance training across the exercise continuum. Sports Health 2013; 5(6): 500-3.
[http://dx.doi.org/10.1177/1941738113477815] [PMID: 24427423]

[5] Behm DG, Muehlbauer T, Kibele A, Granacher U. Effects of strength training using unstable surfaces on strength, power and balance performance across the lifespan: A systematic review and meta-analysis. Sports Med 2015; 45(12): 1645-69.
[http://dx.doi.org/10.1007/s40279-015-0384-x] [PMID: 26359066]

[6] Akuthota V, Ferreiro A, Moore T, Fredericson M. Core stability exercise principles. Curr Sports Med Rep 2008; 7(1): 39-44.
[http://dx.doi.org/10.1097/01.CSMR.0000308663.13278.69] [PMID: 18296944]

[7] Lawrence MA, Carlson LA. Effects of an unstable load on force and muscle activation during a parallel back squat. J Strength Cond Res 2015; 29(10): 2949-53.
[http://dx.doi.org/10.1519/JSC.0000000000000955] [PMID: 25844869]

[8] Nairn BC, Sutherland CA, Drake JD. Location of instability during a bench press alters movement patterns and electromyographical activity. J Strength Cond Res 2015; 29(11): 3162-70.
[http://dx.doi.org/10.1519/JSC.0000000000000973] [PMID: 25932979]

[9] Willardson JM. The effectiveness of resistance exercises performed on unstable equipment. Strength Condit J 2004; 26(5): 70-4.
[http://dx.doi.org/10.1519/00126548-200410000-00015]

[10] Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. Sports Med 2006; 36(3): 189-98.
[http://dx.doi.org/10.2165/00007256-200636030-00001] [PMID: 16526831]

[11] Leetun DT, Ireland ML, Willson JD, Ballantyne BT, Davis IM. Core stability measures as risk factors for lower extremity injury in athletes. Med Sci Sports Exerc 2004; 36(6): 926-34.
[http://dx.doi.org/10.1249/01.MSS.0000128145.75199.C3] [PMID: 15179160]

[12] Willson JD, Dougherty CP, Ireland ML, Davis IM, McClay I. Core stability and its relationship to lower extremity function and injury. J Am Acad Orthop Surg 2005; 13(5): 316-25.
[http://dx.doi.org/10.5435/00124635-200509000-00005] [PMID: 16148357]

[13] Willardson JM. Core stability training: Applications to sports conditioning programs. J Strength Cond Res 2007; 21(3): 979-85.
[PMID: 17685697]

[14] Hibbs AE, Thompson KG, French D, Wrigley A, Spears I. Optimizing performance by improving core stability and core strength. Sports Med 2008; 38(12): 995-1008.
[http://dx.doi.org/10.2165/00007256-200838120-00004] [PMID: 19026017]

[15] Huxel Bliven KC, Anderson BE. Core stability training for injury prevention. Sports Health 2013; 5(6): 514-22.
[http://dx.doi.org/10.1177/1941738113481200] [PMID: 24427426]

[16] Schmidtbleicher D. Applying the theory of strength development. Track Field Quart Rev 1987; 87: 34-44.

[17] Schmidtbleicher D, Buehrle M. Neuronal adaptation and increase of cross-sectional area studying different strength training methods. In: Jonsson B, Ed. Biomechanics X-B. Champaign, IL: Human Kinetics 1987; pp. 615-20.

[18] Anderson KG, Behm DG. Maintenance of EMG activity and loss of force output with instability. J Strength Cond Res 2004; 18(3): 637-40.
[PMID: 15320684]

[19] Goodman CA, Pearce AJ, Nicholes CJ, Gatt BM, Fairweather IH. No difference in 1RM strength and muscle activation during the barbell chest press on a stable and unstable surface. J Strength Cond Res 2008; 22(1): 88-94.
[http://dx.doi.org/10.1519/JSC.0b013e31815ef6b3] [PMID: 18296960]

[20] Dunnick DD, Brown LE, Coburn JW, Lynn SK, Barillas SR. Bench press upper-body muscle activation between stable and unstable loads. J Strength Cond Res 2015; 29(12): 3279-83.
[http://dx.doi.org/10.1519/JSC.0000000000001198] [PMID: 26540024]

[21] Aranda LC, Mancini M, Werneck FZ, Da Silva Novaes J, Da Silva-Grigoletto ME, Vianna JM. Electromyographic activity and 15RM load during resistance exercises on stable and unstable surfaces. JEPonline 2016; 19(1): 114-23.

[22] Saeterbakken AH, Fimland MS. Electromyographic activity and 6RM strength in bench press on stable and unstable surfaces. J Strength Cond Res 2013; 27(4): 1101-7.
[http://dx.doi.org/10.1519/JSC.0b013e3182606d3d] [PMID: 22692120]

[23] Kohler JM, Flanagan SP, Whiting WC. Muscle activation patterns while lifting stable and unstable loads on stable and unstable surfaces. J Strength Cond Res 2010; 24(2): 313-21.
[http://dx.doi.org/10.1519/JSC.0b013e3181c8655a] [PMID: 20072068]

[24] Anderson K, Behm DG. Trunk muscle activity increases with unstable squat movements. Can J Appl Physiol 2005; 30(1): 33-45.
[http://dx.doi.org/10.1139/h05-103] [PMID: 15855681]

[25] Saeterbakken AH, Fimland MS. Muscle force output and electromyographic activity in squats with various unstable surfaces. J Strength Cond Res 2013; 27(1): 130-6.
[http://dx.doi.org/10.1519/JSC.0b013e3182541d43] [PMID: 22450254]

[26] Patterson JM, Vigotsky AD, Oppenheimer NE, Feser EH. Differences in unilateral chest press muscle activation and kinematics on a stable *versus* unstable surface while holding one *versus* two dumbbells. PeerJ 2015; 3: e1365.
[http://dx.doi.org/10.7717/peerj.1365] [PMID: 26528421]

[27] Prieske O, Muehlbauer T, Mueller S, *et al.* Effects of surface instability on neuromuscular performance during drop jumps and landings. Eur J Appl Physiol 2013; 113(12): 2943-51.
[http://dx.doi.org/10.1007/s00421-013-2724-6] [PMID: 24072033]

[28] Behm DG, Leonard AM, Young WB, Bonsey WA, MacKinnon SN. Trunk muscle electromyographic activity with unstable and unilateral exercises. J Strength Cond Res 2005; 19(1): 193-201.
[PMID: 15705034]

[29] Marshall PW, Murphy BA. Increased deltoid and abdominal muscle activity during Swiss ball bench press. J Strength Cond Res 2006; 20(4): 745-50.
[PMID: 17194238]

[30] Norwood JT, Anderson GS, Gaetz MB, Twist PW. Electromyographic activity of the trunk stabilizers during stable and unstable bench press. J Strength Cond Res 2007; 21(2): 343-7.
[PMID: 17530936]

[31] Borreani S, Calatayud J, Martin J, Colado JC, Tella V, Behm DG. Exercise intensity progression for exercises performed on unstable and stable platforms based on ankle muscle activation 2013. Gait Posture 2014; 39(1): 404-9.
[http://dx.doi.org/10.1016/j.gaitpost.2013.08.006] [PMID: 23999147]

[32] Sangwan S, Green RA, Taylor NF. Characteristics of stabilizer muscles: A systematic review. Physiother Can 2014; 66(4): 348-58.
[http://dx.doi.org/10.3138/ptc.2013-51] [PMID: 25922556]

[33] Campbell BM, Kutz MR, Morgan AL, Fullenkamp AM, Ballenger R. An evaluation of upper-body muscle activation during coupled and uncoupled instability resistance training. J Strength Cond Res 2014; 28(7): 1833-8.
[http://dx.doi.org/10.1519/JSC.0000000000000350] [PMID: 24950226]

[34] Ostrowski SJ, Carlson LA, Lawrence MA. Effect of an unstable load on primary and stabilizing muscles during the bench press. J Strength Cond Res 2017; 31(2): 430-4.
[http://dx.doi.org/10.1519/JSC.0000000000001497] [PMID: 27564994]

[35] Panza P, Aranda LC, Damasceno VO, *et al.* Energy Cost, Number of maximum repetitions, and rating of perceived exertion in resistance exercise with stable and unstable platforms. JEPonline 2014; 17(3): 77-87.

[36] Granacher U, Schellbach J, Klein K, Prieske O, Baeyens JP, Muehlbauer T. Effects of core strength training using stable *versus* unstable surfaces on physical fitness in adolescents: A randomized controlled trial. BMC Sports Sci Med Rehabil 2014; 6(1): 40.
[http://dx.doi.org/10.1186/2052-1847-6-40] [PMID: 25584193]

[37] Chulvi-Medrano I, Martínez-Ballester E, Masiá-Tortosa L. Comparison of the effects of an eight-week push-up program using stable *versus* unstable surfaces. Int J Sports Phys Ther 2012; 7(6): 586-94.
[PMID: 23316422]

[38] Marinkovic M, Bratic M, Ignjatovic A, Radovanovic D. Effects of 8-week instability resistance training on maximal strength in inexperienced young individuals. Serb J Sports Sci 2012; 6(1): 17-21.

[39] Behm DG, Drinkwater EJ, Willardson JM, Cowley PM. Canadian Society for Exercise Physiology position stand: The use of instability to train the core in athletic and nonathletic conditioning. Appl Physiol Nutr Metab 2010; 35(1): 109-12.
[http://dx.doi.org/10.1139/H09-128] [PMID: 20130673]

[40] Krause DA, Jacobs RS, Pilger KE, Sather BR, Sibunka SP, Hollman JH. Electromyographic analysis of the gluteus medius in five weight-bearing exercises. J Strength Cond Res 2009; 23(9): 2689-94.
[http://dx.doi.org/10.1519/JSC.0b013e3181bbe861] [PMID: 19910807]

[41] Tyler TF, Nicholas SJ, Campbell RJ, McHugh MP. The association of hip strength and flexibility with the incidence of adductor muscle strains in professional ice hockey players. Am J Sports Med 2001; 29(2): 124-8.
[PMID: 11292035]

[42] O'Connor D. Groin injuries in professional rugby league players: A prospective study. J Sports Sci 2004; 22(7): 629-36.
[http://dx.doi.org/10.1080/02640410310001655804] [PMID: 15370493]

[43] Maffey L, Emery C. What are the risk factors for groin strain injury in sport? A systematic review of the literature. Sports Med 2007; 37(10): 881-94.
[http://dx.doi.org/10.2165/00007256-200737100-00004] [PMID: 17887812]

[44] Hrysomallis C. Hip adductors' strength, flexibility, and injury risk. J Strength Cond Res 2009; 23(5): 1514-7.
[http://dx.doi.org/10.1519/JSC.0b013e3181a3c6c4] [PMID: 19620912]

[45] Hölmich P, Maffey L, Emery C. Preventing groin injuries. In: Bahr R, Engebretsen L, Eds. Handbook of Sports Medicine and Science: Sports Injury Prevention. Chichester, UK: Wiley & Blackwell 2009; pp. 91-113.
[http://dx.doi.org/10.1002/9781444303612.ch7]

[46] Quinn A. 2010.

[47] Kemp JL, Schache AG, Makdissi M, Sims KJ, Crossley KM. Greater understanding of normal hip physical function may guide clinicians in providing targeted rehabilitation programmes. J Sci Med Sport 2013; 16(4): 292-6.
[http://dx.doi.org/10.1016/j.jsams.2012.11.887] [PMID: 23266242]

[48] Griffin VC, Everett T, Horsley IG. A comparison of hip adduction to abduction strength ratios, in the dominant and non-dominant limb, of elite academy football players. J Biomed Engineering Informatics 2016; 2(1): 109-18.
[http://dx.doi.org/10.5430/jbei.v2n1p109]

[49] Hay JG. The Biomechanics of Sports Techniques. Englewood Cliffs, NJ: Prentice Hall Inc. 1985; pp. 12-68.

[50] Bornholdt S. Expectation Bubbles in a Spin Model of Markets: Intermittency from Frustration Across Scales. Int J Mod Phys C 2001; 12: 667-74.
[http://dx.doi.org/10.1142/S0129183101001845]

[51] Bovier A, den Hollander F. Metastability: A Potential-Theoretic Approach. Berlin: Springer 2015.
[http://dx.doi.org/10.1007/978-3-319-24777-9]

[52] Kivelson D, Reiss H. Metastable systems in thermodynamics: Consequences, role of constraints. J Phys Chem B 1999; 103: 8337-43.
[http://dx.doi.org/10.1021/jp990960b]

[53] Preis T, Schneider JJ, Stanley HE. Switching processes in financial markets. Proc Natl Acad Sci USA 2011; 108(19): 7674-8.
[http://dx.doi.org/10.1073/pnas.1019484108] [PMID: 21521789]

[54] Noé F, Horenko I, Schütte C, Smith JC. Hierarchical analysis of conformational dynamics in biomolecules: Transition networks of metastable states. J Chem Phys 2007; 126(15): 155102.
[http://dx.doi.org/10.1063/1.2714539] [PMID: 17461666]

[55] Berglund N, Gentz B. Metastability in simple climate models: Pathwise analysis of slowly driven Langevin equations. Stoch Dyn 2002; 2: 327-56.
[http://dx.doi.org/10.1142/S0219493702000455]

[56] Stillinger FH. A topographic view of supercooled liquids and glass formation. Science 1995; 267(5206): 1935-9.
[http://dx.doi.org/10.1126/science.267.5206.1935] [PMID: 17770102]

[57] Kinniment DJ. Synchronization and Arbitration in Digital Systems. Hoboken, NJ: Wiley 2008.

[58] Horstmann JU, Eichel R, Coates RL. Metastability behavior of CMOS ASIC flip-flops in theory and test. IEEE J Solid-State C 1989; 24: 146-57.
[http://dx.doi.org/10.1109/4.16314]

[59] Friston KJ. Transients, metastability, and neuronal dynamics. Neuroimage 1997; 5(2): 164-71.
[http://dx.doi.org/10.1006/nimg.1997.0259] [PMID: 9345546]

[60] Tognoli E, Kelso JA. The metastable brain. Neuron 2014; 81(1): 35-48.
[http://dx.doi.org/10.1016/j.neuron.2013.12.022] [PMID: 24411730]

[61] Rabinovich MI, Huerta R, Varona P, Afraimovich VS. Transient cognitive dynamics, metastability, and decision making. PLOS Comput Biol 2008; 4(5): e1000072.
[http://dx.doi.org/10.1371/journal.pcbi.1000072] [PMID: 18452000]

[62] Lauro Grotto R, Guazzini A, Bagnoli F. Metastable structures and size effects in small group dynamics. Front Psychol 2014; 5: 699.
[http://dx.doi.org/10.3389/fpsyg.2014.00699]

[63] Chow JY, Davids K, Button C, Rein R, Hristovski R, Koh M. Dynamics of multi-articular coordination in neurobiological systems. Nonlinear Dyn Psychol Life Sci 2009; 13(1): 27-55.
[PMID: 19061544]

[64] Balague N, Torrents C, Hristovski R, Davids K, Araújo D. Overview of complex systems in sport. J Syst Sci Complex 2013; 26: 4-13.
[http://dx.doi.org/10.1007/s11424-013-2285-0]

[65] Kelso JA. Coordination dynamics. In: Meyers RA, Ed. Encyclopedia of Complexity and System Science. Heidelberg: Springer 2009; pp. 1537-64.
[http://dx.doi.org/10.1007/978-0-387-30440-3_101]

[66] Hristovski R, Davids K, Araújo D, Button C. How boxers decide to punch a target: Emergent behaviour in nonlinear dynamical movement systems. J Sports Sci Med 2006; 5(CSSI): 60-73.
[PMID: 24357978]

[67] Pinder RA, Davids K, Renshaw I. Metastability and emergent performance of dynamic interceptive actions. J Sci Med Sport 2012; 15(5): 437-43.
[http://dx.doi.org/10.1016/j.jsams.2012.01.002] [PMID: 22326853]

[68] James EG. Metastable postural coordination dynamics. Neurosci Lett 2013; 548: 176-80.
[http://dx.doi.org/10.1016/j.neulet.2013.05.068] [PMID: 23769730]

[69] Davids K, Araújo D, Hristovski R, Pasos P, Chow JY. Ecological Dynamics and Motor Learning Design in Sport. In: Hodges NJ, Williams M, Eds. Skill acquisition in sports: Research, Theory, and Practise. London: Routledge 2012; pp. 112-30.

[70] England SA, Granata KP. The influence of gait speed on local dynamic stability of walking. Gait Posture 2007; 25(2): 172-8.
[http://dx.doi.org/10.1016/j.gaitpost.2006.03.003] [PMID: 16621565]

[71] Martini FH, Nath JL. Fundamentals of Anatomy and Physiology. 8th ed. Pearson, NJ: Benjamin Cummings, 2008: 184-312.

[72] Hodges PW, Gurfinkel VS, Brumagne S, Smith TC, Cordo PC. Coexistence of stability and mobility in postural control: Evidence from postural compensation for respiration. Exp Brain Res 2002; 144(3): 293-302.
[http://dx.doi.org/10.1007/s00221-002-1040-x] [PMID: 12021811]

[73] Loram ID, Lakie M. Human balancing of an inverted pendulum: Position control by small, ballistic-like, throw and catch movements. J Physiol 2002; 540(Pt 3): 1111-24.
[http://dx.doi.org/10.1113/jphysiol.2001.013077] [PMID: 11986396]

[74] Loram ID, Maganaris CN, Lakie M. Human postural sway results from frequent, ballistic bias impulses by soleus and gastrocnemius. J Physiol 2005; 564(Pt 1): 295-311.
[http://dx.doi.org/10.1113/jphysiol.2004.076307] [PMID: 15661824]

[75] Blickhan R, Seyfarth A, Geyer H, Grimmer S, Wagner H, Günther M. Intelligence by mechanics. Philos Trans A Math Phys Eng Sci 2007; 365(1850): 199-220.
[http://dx.doi.org/10.1098/rsta.2006.1911] [PMID: 17148057]

[76] Hasan Z. The human motor control system's response to mechanical perturbation: Should it, can it, and does it ensure stability? J Mot Behav 2005; 37(6): 484-93.
[http://dx.doi.org/10.3200/JMBR.37.6.484-493] [PMID: 16280319]

[77] Knudson D. Fundamentals of Biomechanics. 2nd ed. New York, NY: Springer Publishers 2007; pp. 48-164.

[78] Bartlett R. Introduction to Sports Biomechanics Analyzing Human Movement Patterns. 2nd ed. London: Routledge 2007; pp. 218-20.

[79] Kibele A, Granacher U, Muehlbauer T, Behm DG. Stable, unstable and metastable states of equilibrium: Definitions and applications to human movement. J Sports Sci Med 2015; 14(4): 885-7.
[PMID: 26664288]

[80] Morrissey MC, Harman EA, Johnson MJ. Resistance training modes: Specificity and effectiveness. Med Sci Sports Exer 1995; 27(5): 648-60.
[http://dx.doi.org/10.1249/00005768-199505000-00006] [PMID: 7674868]

[81] Sale DG, Martin JE, Moroz DE. Hypertrophy without increased isometric strength after weight training. Eur J Appl Physiol Occup Physiol 1992; 64(1): 51-5.
[http://dx.doi.org/10.1007/BF00376440] [PMID: 1735412]

[82] Kibele A, Behm DG. Seven weeks of instability and traditional resistance training effects on strength, balance and functional performance. J Strength Cond Res 2009; 23(9): 2443-50.
[http://dx.doi.org/10.1519/JSC.0b013e3181bf0489] [PMID: 19952576]