Relation between bimanual coordination and whole-body balancing on a slackline

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Abstract

To reveal the fundamental skills involved in slacklining, this study examined a hypothesis regarding single-leg standing on a slackline. In the field of practice, instructors teach learners how to maintain balance on a swinging flat belt (slackline), such as by moving their hands in parallel. We hypothesized that bimanual coordination in the horizontal direction might contribute to dynamic balancing on a slackline. In our pilot study, two participants at different skill levels were asked to maintain their balance on a slackline as long as possible. The dynamic stability of bimanual coordination was assessed by a nonlinear time series analysis (cross recurrence quantification analysis), then compared among the participants. Bimanual coordination stability was higher in the experienced player than in the novice player. The results suggest that the single-leg standing skill might be correlated with bimanual coordination stability. Further investigations are expected to clarify this notion in the future.

Keywords: slackline; balance sport; dynamic stability; whole-body coordination; self-organization

Introduction

Slacklining

A slackline is a flat belt that is fixed between two anchor points. Because it bounces and swings in all directions, it is very difficult for beginners to maintaining balance on it. Slacklining exists in two main forms, as balance training and as a competitive balance sport. The latter form first started around 2007 in Europe and has spread to other parts of the world. International contests have been held in which the competitors display various acrobatic skills. Slacklining has also received much attention as a method of balance training, not only for top-level athletes (e.g., Olympic ski jumpers), but also for the elderly or those with motor disorders and are participating in rehabilitation (one of the present authors has used slackline training for rehabilitation). Compared with traditional balance training with a balance ball or beam, we consider, slackline training is enjoyable as a sport or leisure pursuit and can be a sustainable lifelong activity.

Although slacklining has progressed in both its training and competitive forms, academic research on the topic has been limited. Most existing research has examined the effect of slackline training on balancing ability (e.g., Granacher et al., 2010). Although these studies are important to obtain evidence on the effects of slackline training on balance abilities, the skills involved in slacklining remain unclear. Beginners in slackline training experience considerable difficulty in understanding how to start and develop their skill. One study addressed questions of skill but only through a case study that investigated the specific situation of balance recovery after perturbation (Huber & Kleindl, 2010). The fundamental skills required for slacklining have not yet been investigated rigorously.

In this study, we assumed that single-leg standing on the slackline is an essential skill for successful slacklining. This is the first ones used when being instructed in slackline training (e.g., Keller et al., 2012). In practical training, after mastering this ability without support, beginners are encouraged to proceed to the next step, such as walking on a slackline. Therefore, in the present study we chose to experimentally investigate the single-leg standing task as a fundamental skill for slacklining.

Whole-body dynamic balancing

With regard to maintaining postural balance, one might argue that a static balancing strategy, involving the absolute straining of muscles and fixing of joints as if one's body were an inanimate object consisting of rigid materials, is one possible approach. In fact, traditional postural balance studies have assumed such a static model and have often used a *quiet standing task* to evaluate balancing ability (e.g., Winter, 1995). Those studies have also applied static indexes such as the trajectory length of the center of pressure, concluding that shorter lengths are more stable. According to such a static model and indexes, less movement is interpreted as indicating greater stability of the human postural system (e.g., Horak, 1989).

This static balance model, however, is not in accordance with the fact that living systems always fluctuate in various time scales at different levels, from the microscopic level (e.g., the cell) to the macroscopic level (e.g., the skeleton). Such an intrinsic fluctuation can be observed even in a quiet standing task (Balasubramaniam & Wing, 2002). Recent studies of human postural balance have demonstrated the relevance of dynamic balancing (e.g., Delignières, Torre, & Bernard, 2011; Michael a Riley & Turvey, 2002). In these studies, human postural sway is regarded not as meaningless random noise at the musculoskeletal level but as having a meaningful structure emerging from interactions among components in the body-environment system.

Furthermore, it is difficult to investigate whole-body dynamic balancing by means of the quiet standing task paradigm, because quiet standing does not require participants to actively use their whole-body including the upper limbs. In our daily behavior, we often stand and walk on various unstable environments (e.g., sloped ground, bumpy roads, suspension bridges, and so on). Such unstable environments require us to maintain balance dynamically with whole-body coordination, including bimanual coordination of the upper limbs. While one is on a slackline, dynamic balancing with whole-body coordination is more critical because the fluctuation generated by one's own body movement can easily cause amplification of the line's fluctuation, causing one to fall off. Explaining how one maintains balance on a slackline by a static balance strategy is difficult, given the intrinsic fluctuation of an embodied system consisting of so many non-rigid components at different timescales.

Emergence of stable coordination pattern

The human body has a vast range of components (i.e., degrees of freedom: DoFs), from the microscopic cell level (10^{14}) to the macroscopic joint level (10^{2}) (Bernstein, 1967; Turvey, 1990). The *DoF problem* suggested that the large number of independently controllable DoFs places a computational burden on the central nervous system (Turvey, 1990). This indicates the limitations of the unidirectional top-down motor control model, represented metaphorically in terms of computer information processing. In addition, with regard to whole-body movement, solving the DoF problem becomes more difficult because many DoFs need to be considered in a whole-body system. Bernstein, who proposed the DoF problem, suggested as a possible solution that each component (DoF) is coordinated and coupled with other components to organize a functional structure (i.e., *synergy*) rather than being controlled separately (Bernstein, 1967).

Subsequent to Bernstein's suggestion of synergy, an alternative derived from self-organization theory, known as the *dynamical systems approach*, has been widely applied to human movement studies and in other areas of cognitive science. Compared to the traditional cognitive approach that assumes internal computation and prescription in the brain, dynamical systems approach focuses more on interactions between the body (including the brain), environment, and task. Movement or coordination patterns are then theorized as emerging through interactions among several constraints within organism, environment, and task (Davids, Button, & Bennett, 2008; Newell, 1986). The large number of DoFs in an embodied system can be reduced in order to satisfy these constraints. Thus, the functional structure (i.e., *synergy*) to achieve the task emerges as a particular coordination pattern. The individual organism regulates its behavior in order to satisfy the task demands that must be performed in a specific environment.

Indeed, in the framework of *synergetics* (Haken, 1978), a self-organization theory, a system's low-dimensional spatial temporal patterns at the macroscopic level emerge through interactions among components (DoFs) at the microscopic level under constraints from the system's environment or embedded context. The macroscopic pattern also constrains the components' behavior at the microscopic level to keep the pattern stable (Kelso, 1995). Kelso and his colleagues applied *synergetics* to the modelling of bimanual coordination (Haken, Kelso, & Bunz, 1985). The model can describe the qualitative change of pattern within a system by using the concepts of *synergetics*. Rhythmic coordinated behaviors, such as inter-limb coordination, can be modeled as a motion equation (Haken et al., 1985). Recently, dynamical systems approach has not only provided a theoretical framework but also obtained evidence by analytical tools (e.g., fractal analysis and recurrence analysis) based on nonlinear dynamics theory (Holden, Riley, Gao, & Torre, 2013; Van Orden & Riley, 2005). The present study also applies these frameworks and techniques to investigate dynamic balancing skill in slacklining.

Current hypotheses

Based on slackline instructors' experience, here, we propose three hypotheses related to the skill of single-leg standing on a slackline. To maintain whole-body balance in an unstable environment (i.e., on the slackline), the overall task is regarded as keeping the center of mass (COM) above the base of support (i.e., the place where one's foot contacts the line)(Shumway-Cook & Woollacott, 2013). To satisfy this task demand, components of the embodied system are supposed to self-organize. The hypothesized control strategy proceeds as follows:

1) in a horizontal direction, one should raise both hands high and coordinate them in parallel in order to regulate the COM's position above the line;
2) in the vertical direction, one should flexibly bend his/her knee to compensate for the line's fluctuations;
3) in the anteroposterior direction, one should maintain a straight back to keep the center of gravity vertically balanced over the sole of the foot standing on the line.

These three hypotheses are depicted by the three pictures in Figure 1. In the current article, we focused on the first hypothesis. As shown in Figure 1 (4), we hypothesize that fluctuations from the line might be canceled or absorbed by compensating strategy between both hands and the COM positions. According to this hypothesis, if the position of

COM moves to right, coupled both hands move to left so as to counter-balance. Such strategy enables one to regulate whole-body balance flexibly using two DoFs (both hands and COM positions) against the line fluctuations. We suppose that such a compensating relation realizes a functional unit as a *synergy* (Latash, 2008). Furthermore, at this moment, bimanual coordination is supposed to play an important role, because if left and right hands move individually, both hands' position cannot compensate the COM's position efficiently. So we consider bimanual coordination in terms of coupled oscillator that can be regarded as a single system and its dynamic stability as the hypothesized variable to test the first hypothesis. The current article reports partial results of testing it.

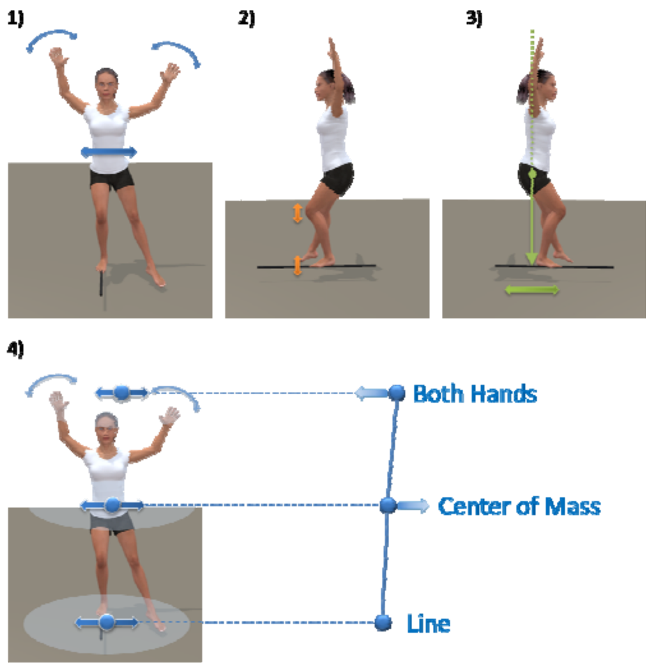

Figure 1 Current hypotheses: regulating whole-body posture in the 1) horizontal, 2) vertical, 3) anteroposterior direction, 4) compensational relation between both hands and COM against the line.

Method

Participants

Two participants, an experienced player (age 40, male) and a novice player (age 30, male), were recruited to make possible comparisons between slacklining performances at different skill levels. The experienced player had more than three years of experience in slacklining, whereas the novice player had just started slacklining. The experimental procedures were approved by the research ethics committee of Kanagawa University, where the experiment was conducted. Each participant provided informed consent to participate in this study.

Apparatus

Slacklining was performed on SLACKRACK300 (GIBBON SLACKLINES, 300 cm length, 30 cm height). A 3D motion capture system (OptiTrack V120: Trio, NaturalPoint, Inc.) was used to measure participants' body movement (sampling frequency: 120 Hz). Nine reflective markers ware attached to the top of the head, the front of the head, the tips of the index fingers, the COM (around the hip), the tops of the knees, and the ankles. Three-dimensional time series data of each marker were smoothed by a second-order Butterworth low-pass filter with a 12 Hz cutoff frequency.

Procedure

The experimental task was to perform single-leg standing while on a slackline. Participants were required to maintain balance on the slackline for as long as possible, using their preferred leg. Each trial lasted for three minutes, including rest breaks. Participants underwent five trials.

Data Analysis

To evaluate single-leg standing skill, we calculated persistence time, or how long the participant could stay on the line before falling off, by the following procedure. If he maintained the task for at least five seconds, it was regarded as a *success*; if he fell off before five seconds had passed, that effort was a *failure*. For each instance of success, the length of time on the line was measured. It was expected, of course, that the experienced player would have a longer persistence time than the novice.

To analyze 3D motion capture data quantitatively, time series data were processed as follows. Among the instances of success, those when the player stayed on the line for at least 15 seconds were defined as *steady*. The first five and the last five seconds of each steady instance were omitted because participants were more likely to have balance difficulties in the initiating and ending phases of each attempt, with the result that the data from these phases were often not steady. Finally, the remaining time series data on the steady attempts were divided into five seconds section. After we had collected all data satisfying the above conditions, the data were smoothed and analyzed by the following nonlinear time series analysis method.

To quantify stability of movement (i.e., bimanual coordination), *cross-recurrence quantification analysis* (CRQA; Zbilut, Giuliani, and Webber, 1998) was applied. This is a nonlinear time series analysis method that captures the recurring properties and patterns of a dynamical system that results from two streams of information interacting over time (Zbilut et al., 1998) and quantifies how similarly the two observed data series unfold over time (Shockley, 2005). Recurrence quantification analysis was originally developed to uncover subtle time correlations and repetitions of patterns, and it is relatively free of assumptions about data size and distribution (Zbilut & Webber, 1992). In CRQA, two time-delayed copies of the original time series were used for embedding the data in higher dimensional space, reconstructing the phase space, to analyze the recurrent structure between them (Zbilut et al., 1998).

Within the framework of dynamical systems approach, for inter-limb rhythmic coordination, two CRQA measures are regarded as significant indexes of stability of movement (Pellecchia, Shockley, & Turvey, 2005; Shockley, 2005). The percent recurrence (%REC) in CRQA corresponds to the ratio of the actual number of shared locations to the number of possible shared locations in phase space. It provides an index of the magnitude of stochastic noise in the system (Pellecchia et al., 2005); a higher %REC indicates less noise in the system. The other measure was related to the line structure calculated from the recurrence plot, Maxline (MAXL). MAXL is the longest shared trajectory in phase space and the length of the maximum diagonal line on the plot (Webber & Zbilut, 2005). MAXL is a measure of the stability of the shared activity (Shockley, 2005). It is supposed to provide an index of the system's sensitivity to perturbations (i.e., the strength of the attractor against perturbations) (Pellecchia et al., 2005).

We performed CRQA using the R package "crqa" (version 1.0.6) (Coco & Dale, 2014) after determining the optimal values for the input parameters (e.g., time delay, embedding dimensions, radius) with reference to the standard guidelines of the RQA method (Webber & Zbilut, 2005).Consequently, we chose parameters of 20 for time delay, 3 for embedding dimensions, and 25 for radius (with z-score normalization and maximum distance rescaling; Webber & Zbilut, 2005).

Results

Figure 2 presents the persistence time in the single-leg standing task for each participant. The average persistence time was longer for the experienced player (107.25 sec) than for the novice player (20.39 sec), reflecting the experienced player's far greater skill.

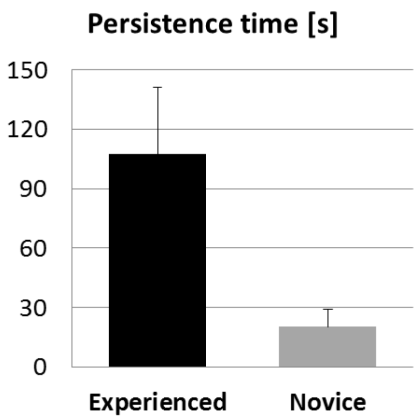

Figure 2 Persistence time in the single-leg standing task (Error bar: Standard deviation)

Figure 3 represents sample raw data from 20-second time series of both hands in the horizontal direction for each participant: top, experienced player, bottom, novice player. The x- and y-axes represent time [sec] and position [m], respectively. Black rigid and dashed lines represent left- and right- hand motion, respectively. Blue rigid line shows the COM's motion.

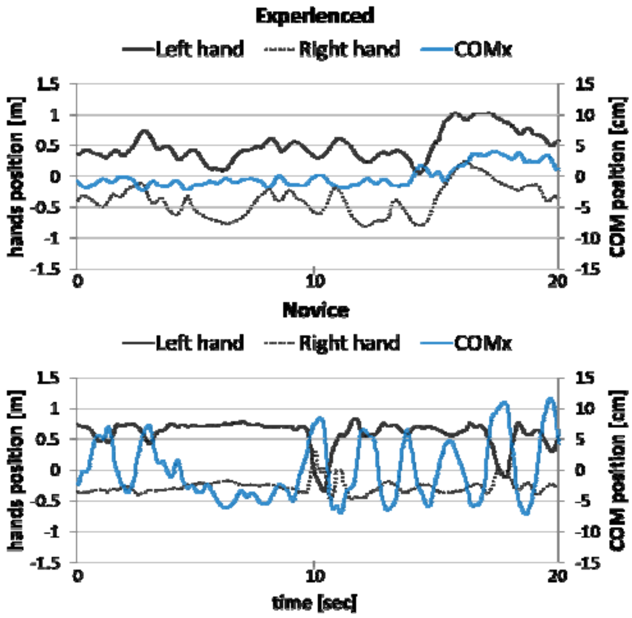

Figure 3 Sample 20 sec. time series of both hands for the two participants (top: experienced player, bottom: novice)

Figure 4 shows %REC for each participant in bimanual coordination. %REC was higher for the experienced player (22.95%) than for the novice player (17.01%). Figure 5 shows MAXL for each participant in bimanual coordination. MAXL was longer for the experienced player (126.37) than for the novice player (70.67).

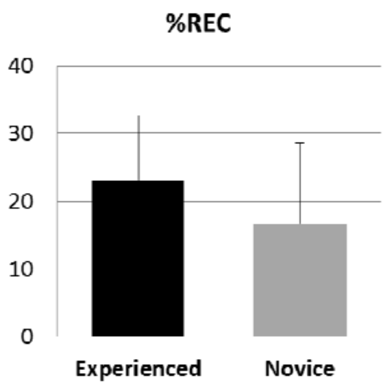

Figure 4 Percent recurrence for each player (Error bar: Standard deviation)

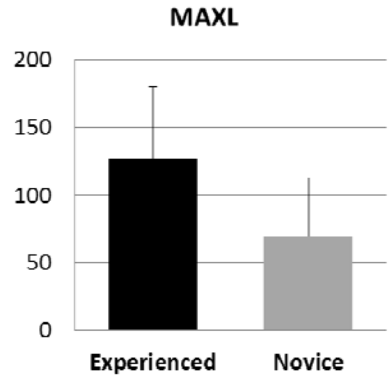

Figure 5 Maxline for each player
(Error bar: Standard deviation)

Discussion

As shown in Figure 2, the experienced player had greater single-leg standing skill than the novice player. This result is consistent with the prediction that persistence time should be longer for high-level than for low-level players. It confirms that the two players were at different skill levels.

As shown by the sample time series of both hands (Figure 3), it seems that the experienced player could maintain a more stable bimanual coordination pattern in parallel than the novice player. In other words, the experienced player can move their hands in the same way keeping a constant relation between hands. Whereas their hands move in the opposite way to the COM motion as if compensating each other or counter-balancing. Although bimanual movement of the experienced player seems to be apparently larger than that of the novice player, it moves more rhythmically or oscillatory than that of the novice player. In other words, bimanual movement of the experienced player seems to be more dynamically stable. On the other hand, the novice player could not consistently maintain a particular bimanual coordination pattern; in fact, he broke his bimanual coordination pattern and crossed the hands twice. Bimanual movement of the novice player seems to move less rhythmically and be less dynamically stable. The COM position of the novice player is also more variable than that of the experienced player. As a result of comparing two participants' behaviors, our hypotheses on compensating relation between both hands and COM positions (Figure 1) seems to be supported as far as observed in sample time series of Figure 3.

The CRQA for bimanual coordination found that %REC and MAXL were greater in the experienced player than in the novice player. These results indicate that bimanual coordination during the single-leg standing task was more stable in the experienced player than in the novice player in terms of both the magnitude of noise in the system and the system's sensitivity to perturbations. This fact supports our first hypothesis. Further experiments should be conducted to obtain more samples and test the hypothesis quantitatively. It will also be necessary to investigate the relation between bimanual coordination and whole-body dynamic balancing by quantifying the coupling between bimanual coordination and the line as well as the actual COM horizontal position. Although the causal relation between bimanual coordination and whole-body balancing is also important and should be examined, it might not be so simple. It is difficult to reveal whether bimanual coordination causes whole-body balancing and otherwise because such a phenomenon might have an emergent property that cannot be reduced to a particular factor simply.

Although our pilot study is a case study recruiting only two participants, the results suggest that dynamic balancing skill on a slackline is correlated with bimanual coordination stability. Thus, our hypothesis seemed to be partially supported. In the future, we intend to examine a specific relationship among the skill and hypothesized variables quantitatively. That is, we wish to investigate whether bimanual coordination contributes to dynamic balancing on a slackline and, if so, how it contributes and how experienced players acquire this skill. We plan to conduct an experiment comparing two groups of different skill levels (i.e., expert vs. novice) with more samples. The future experiment should conduct not only statistical test comparing two groups but also analysis of relation between bimanual coordination and whole-body balancing.

In the practical fields of sports training and rehabilitation, slacklining is expected to improve dynamic balancing skill (Kodama, Yamagiwa, & Kikuchi, 2015). Slacklining requires one to activate inner muscles, that supports a fundamental level of action and involves the regulation of muscle tone (Bernstein, 1996), rather than outer muscles. We suppose that slackline balance training might improve the sensitivity to dynamic changes in the environment and in one's own body in terms of haptic perception based on muscle sense (Carello, Silva, Kinsella-Shaw, & Turvey, 2008). If so, slacklining can contribute to improvement of haptic perception system through the body. Even though this notion is a matter of speculation, if the present study can reveal the skill for slacklining, we believe it can have implications for the practical fields regarding how to develop dynamic balancing skill based on sensitive haptic perception system.

Conclusion

The purpose of this study was to reveal the fundamental skills required for slacklining. We examined a hypothesis regarding the dynamic balancing skill for slacklining. In the practice of slackline training, instructors impart their knowledge of how to develop this skill to learners, such as by moving their hands in parallel. We hypothesized that bimanual coordination in the horizontal direction might contribute to dynamic balancing on a slackline. In our pilot study, participants at different skill levels were required to maintain single-leg standing on a slackline for as long as possible. The dynamic stability of bimanual coordination was assessed by nonlinear time series analysis (i.e., cross-recurrence quantification analysis) and compared between participants. As expected, persistence time on the line was longer in the experienced player than in the novice player. Also, bimanual coordination stability was higher in the experienced player than in the novice player, in terms of both the magnitude of stochastic noise in the system (i.e., %Recurrence) and the system's sensitivity to perturbations (i.e., Maxline). These results suggest that skilled performance of single-leg standing on a slackline is correlated with bimanual coordination stability. We suppose that bimanual coordination contributes to whole-body dynamic balancing on a slackline. Further investigations are expected to clarify this notion in the future.

References

Balasubramaniam, R., & Wing, A. M. (2002). The dynamics of standing balance. *Trends in Cognitive Sciences*, 6(12), 531–536.

Bernstein, N. A. (1967). *The Co-ordination and regulation of movements*. Pergamon Press Ltd.

Bernstein, N. A. (1996). *Dexterity and Its Development*. Psychology Press.

Carello, C., Silva, P. L., Kinsella-Shaw, J., & Turvey, M. T. (2008). Muscle-based perception: theory, research and implications for rehabilitation. *Revista Brasileira de Fisioterapia*, 12(5), 339–350.

Coco, M. I., & Dale, R. (2014). Cross-recurrence quantification analysis of categorical and continuous time series: an R package. *Frontiers in Psychology*, 5, 510.

Davids, K., Button, C., & Bennett, S. (2008). *Dynamics of Skill Acquisition: A Constraints-led Approach*. Human Kinetics.

Delignières, D., Torre, K., & Bernard, P.-L. (2011). Transition from persistent to anti-persistent correlations in postural sway indicates velocity-based control. *PLoS Computational Biology*, 7(2), e1001089.

Granacher, U., Iten, N., Roth, R., & Gollhofer, a. (2010). Slackline training for balance and strength promotion. *International Journal of Sports Medicine*, 31(10), 717–723.

Haken, H. (1978). *Synergetics: an introduction : nonequilibrium phase transitions and self-organization in physics, chemistry and biology*. Springer-Verlag.

Haken, H., Kelso, J. A. S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics*, 51(5), 347–356.

Holden, J. G., Riley, M. A., Gao, J., & Torre, K. (Eds.). (2013). *Fractal Analyses: Statistical and Methodological Innovations and Best Practices*, Frontiers E-books.

Horak, F. (1989). Components of postural dyscontrol in the elderly : a review . Neurobiol Aging Components of Postural Dyscontrol in the Elderly : A Review. *Neurobiology of Aging*, 10(6), 727–738.

Huber, P., & Kleindl, R. (2010). A case study on balance recovery in slacklining. *ISBS-Conference Proceedings Archive*, (1990), 1–4.

Keller, M., Pfusterschmied, J., Buchecker, M., Müller, E., & Taube, W. (2012). Improved postural control after slackline training is accompanied by reduced H-reflexes. *Scandinavian Journal of Medicine and Science in Sports*, 22(4), 471–477.

Kelso, J. A. S. (1995). *Dynamic Patterns: The Self-organization of Brain and Behavior*. MIT Press.

Kodama, K., Yamagiwa, H., & Kikuchi, Y. (2015). Effects of slackline training on dynamic postural balancing. *Proceedings of Second International Workshop on Skill Science*, 48–49.

Latash, M. L. (2008). *Synergy*. Oxford University Press,.

Newell, K. M. (1986). Constraints on the development of coordination. *Motor Development in Children: Aspects of Coordination and Control*, 34, 341-360.

Pellecchia, G. L., Shockley, K. D., & Turvey, M. T. (2005). Concurrent cognitive task modulates coordination dynamics. *Cognitive Science*, 29(4), 531–57.

Riley, M. a, & Turvey, M. T. (2002). Variability of determinism in motor behavior. *Journal of Motor Behavior*, 34(2), 99–125.

Shockley, K. D. (2005). Cross recurrence quantification of interpersonal postural activity. In M. Riley & G. Van Orden (Eds.), *Tutorials in contemporary nonlinear methods for the behavioral sciences* (pp. 142–177).

Shumway‐Cook, A., & Woollacott, M. H. (2013). *Motor Control: Translating Research Into Clinical Practice*. Lippincott Williams & Wilkins.

Turvey, M. T. (1990). Coordination. *American Psychologist*, 45(8), 938–953.

Van Orden, G. C., & Riley, M. A. (Eds.). (2005). *Tutorials in Contemporary Nonlinear Methods for the Behavioral Sciences*. National Science Foundation.

Webber, C. L., & Zbilut, J. P. (2005). Recurrence quantification analysis of nonlinear dynamical systems. In M. Riley & G. Van Orden (Eds.), *Tutorials in contemporary nonlinear methods for the behavioral sciences* (pp. 26–94).

Winter, D. (1995). Human balance and posture control during standing and walking. *Gait & Posture*, 3(4), 193–214.

Zbilut, J. P., Giuliani, A., & Webber, C. L. (1998). Detecting deterministic signals in exceptionally noisy environments using cross-recurrence quantification. *Physics Letters A*, 246(1-2), 122–128.

Zbilut, J. P., & Webber, C. L. (1992). Embeddings and delays as derived from quantification of recurrence plots. *Physics Letters A*, 171(3-4), 199–203.