Structure of force variability during squats performed with an inertial flywheel device under stable versus unstable surfaces

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1 Keywords

2 Abstract

The use of unstable surfaces during resistance training has demonstrated a maintenance or reduction on force production. However, the use of unstable surface on force variability has not been assessed using non-linear methods that may be better suited to detect changes in movement variability throughout a given movement. Consequently, this study compared the use of stable vs unstable surfaces on force variability during bilateral squats performed with an inertial flywheel device (Eccoteck, Byomedic System SCP, Spain). Twenty healthy men (mean ± SD: age 22.9 ± 2.9 years, height 1.81 ± 0.7 m, body mass 76.4 ± 7.6 kg and 1RM back squat 110.9 ± 19.7 kg) with a minimum of four years in resistance training performed six sets of six repetitions of squats at maximal concentric effort with one minute rest between sets. Force output on the vertical axes was measured using a strain gauge and the results were processed using nonlinear sample entropy (SampEn). Results showed no differences for any of the dependent variables between stable and unstable conditions. SampEn showed no differences between conditions (chi-squared = 0.048 P = 0.827), while Force$_{mean}$ and SampEn presented a small correlation (r = 0.184; p < 0.01). No changes in entropy were found over the course of the series. Together, these results suggest that the structure of force variability between stable and unstable surfaces are similar. This lack of difference between surfaces may be

due to postural and anticipatory adjustments. Consequently, by introducing unstable surfaces to the flywheel bilateral squat exercise, practitioners may not observe changes in $Force_{mean}$ and force variability when compared to stable surface training suggesting that increased training volumes or intensity may be required during unstable environments to cause a desired training stimulus.

3   Introduction

The squat is one of the most frequently used resistance exercises for strength training in both athletic and rehabilitation settings (Slater & Hart, 2017). While traditional methods of resistance training incorporate the use of isotonic external loads (e.g., barbells), alternative methods for providing external resistance can also be used to provide a unique stimulus (Berg & Tesch, 1998). One of the most commonly implemented methods is through the use of rotational resistance (e.g., flywheel training), which generates force by the angular acceleration of a revolving mass. This form of training offers gravity-independent resistance and can be used as a surrogate for traditional resistance training methods (Berg & Tesch, 1998; Norrbrand, Pozzo, & Tesch, 2010). Furthermore, it has been used extensively in previous research and incorporates vertical force being applied through a harness with athletes standing upon a stable surface/platform (de Hoyo et al., 2015; Vázquez-Guerrero & Moras, 2015; Vázquez-Guerrero et al., 2016).

To change the stimulus that is applied in a resistance training exercise, the surface that an exercise is completed upon can be altered and can be made less stable (Anderson & Behm, 2004). To date, studies have demonstrated a maintenance or a reduction in force or power when performing squat exercises during unstable conditions (Behm & Colado, 2012). For example, research by Vazquez et al. (2016) has shown that the use of flywheel devices during the bilateral squat achieved similar mean force outputs under stable and unstable conditions. This lack of difference was attributed to the type of exercise, instability device used, weight lifted, and subject's training background (Zemková, 2017).

Movement variability is defined as the normal variations that occur in motor performance across multiple repetitions of a task (Stergiou & Decker, 2011). This variability limits the ability of an individual to maintain a desired force or to complete an intended limb trajectory (Harris & Wolpert, 1998) and can be affected by the presence of visual feedback (Christou, 2005), task specificity (Christou & Carlton, 2001), force level (Kouzaki, Shinohara, Masani, & Fukunaga, 2004), fatigue (Tracy, Maluf, Stephenson, Hunter, & Enoka, 2005), or the type and the intensity of the muscle contraction, (Enoka et al., 2003). Every time an individual replicates a movement, variance in force production can occur (Oshita & Yano, 2011). Additionally, when investigating movement variability in sports science, research refers to variability as the way that athletes adapt and stabilize their actions according to the environmental, personal and task constraints they face (Davids, Button, & Bennett, 2008; Dias et al., 2014; Silva et al., 2014). This is likely a nonlinear and dynamic phenomenon, therefore, it is difficult to be detected by using conventional linear analysis, as they are limited in detecting dynamic changes in the patterns of force production. Indeed, nonlinear analysis of variability might provide valuable information about spatiotemporal or structural characteristics with nonlinear time series processing methods able to measure predictability and structure variability (Seely & Macklem, 2004).

The measure of entropy is commonly used to describe signal predictability in physical activity (Cavanaugh, Kochi, & Stergiou, 2010), postural control (Deffeyes, Harbourne, Stuberg, & Stergiou, 2011) and human walking data (Rathleff, Samani, Olesen, Kersting, & Madeleine, 2011). Approximate entropy is related to the probability that two sequences, which are similar for n points, remain similar at the next point. Although it has been applied to a variety of physiological and clinical datasets such as electroencephalography (Rezek & Roberts, 1998) and respiratory motion (Burioka et al., 2003) it is a biased statistic because it includes selfmatches (Pincus & Goldberger, 1994; Pincus, 1991). In order to minimize this bias, Richman and Moorman (Richman & Moorman, 2000) developed an alternative method of measuring movement variability described as "sample entropy" (SampEn). The use of SampEn presents higher relative consistency and a lower dependency on data length. In essence, high regularity in the time series is related to low entropy scores, and randomness to high entropy scores (Stergiou, Harbourne, & Cavanaugh, 2006). While previous research has acknowledged movement variability may occur by altering the training surface

during resistance training (Behm & Colado, 2012), the use of advanced methods of assessing movement variability have not been employed.

While previous research has investigated the effects of unstable surfaces on force output during resistance training (Anderson & Behm, 2004; Behm & Colado, 2012), no studies to date have described the structure of force variability using nonlinear techniques. Consequently, the aim of this study was to identify the changes of temporal structure of force variability using nonlinear techniques during the flywheel bilateral squat using stable versus unstable surfaces. It was hypothesized that (a) unstable surfaces would result in higher entropy compared with the stable condition; (b) entropy would not increase in line with increases in force production; and (c) entropy would not change throughout the series performed.

4 Methods

4.1 Experimental approach to the problem

To assess the effects of using stable or unstable surfaces on force variability during the flywheel bilateral squat, a cross-sectional design consisting of two conditions was used that required the subjects to complete six sets of six repetitions at maximal concentric with one minute rest between sets. This protocol was carried out on two different days that was separated by one week using stable or unstable surfaces.

4.2 Subjects

Twenty, healthy, male, physical education students (mean ± standard deviation (SD): age 22.9 ± 2.9 years, height 1.81 ± 0.70 m, body mass 76.4 ± 7.6 kg and one repetition maximum (1RM) back squat 110.9 ± 19.7 kg) volunteered to participate in this study. All subjects had at least four years of resistance training experience, but had no previous experience using a flywheel device. Additionally, subjects had not been utilising unstable conditions within their resistance training programmes. All subjects were informed about the procedures and the possible risks, and gave their informed consent before inclusion. All experimental procedures were approved by the clinical research ethical committee of the local government's sports service, and written informed consent was provided by all subjects before study initiation.

4.3 Procedures

Across two testing occasions that was separated by one week, subjects performed a dynamic bilateral half squat with an inertial flywheel device (Eccoteck, Byomedic System SCP, Barcelona, Spain) under stable and unstable conditions. The bilateral half squat was initiated by moving the hips back and bending the knees and hips to lower the torso, then returning to the upright position. The flywheel consists of a metal flywheel (diameter: 0.42 m) with space for additional mass to be added so that the rotational inertia can be manipulated. A fixed axis is located at the centre of the beam around which the masses rotate. A cone is attached above the flywheel, and as they spin together, a tether winds and unwinds around the cone. To alter the resistance applied, it is possible to modify the moment of inertia by adding any number of the 16 masses (0.421 kg) to the edge of the flywheel and also by selecting four positions (P1, P2, P3 or P4), thus changing the location of the pulley that is closest to the cone. The greatest force outputs are produced in the uppermost position (P1), where the rope winds around the narrowest radius of the cone (the lower arm lever). By contrast, the lowest position (P4) (the higher arm lever), where a wider part of the cone is used to spin the rope, achieves the highest velocities with the lowest force output. In the current study, all 16 masses were used to generate a moment of inertia of 0.27 kg·m2. The pulley closest to the cone was situated at P1 to achieve the maximal force production (Vázquez-Guerrero et al., 2016).

Force output was measured using a strain gauge, with a linear encoder (with a time resolution of 10 ms and an accuracy of 0.075 mm) used to measure the vertical displacement of the participant performing the bilateral squat. Both the strain gauge and the encoder were connected to a MuscleLab 4000e unit (MuscleLab, Ergotest Technology AS, Langesund, Norway). These data were sampled at a frequency of 100 Hz, recorded by the unit and stored on a laptop computer equipped with data analysis software (MuscleLab V8.27). The software displays the force, the time course of displacement, and the velocity. The strain gauge and the cord of the linear encoder were attached to the harness using carabineers. The linear encoder was positioned between the feet, close to the floor pulley. During the exercise, all forces applied to the force transducer were recorded.

Prior to the experimental study, subjects underwent a familiarization session in which the squat with the inertial flywheel device under both stable and unstable conditions was explained and trial sets were carried out. Emphasis was placed on proper exercise technique, the importance of achieving a knee angle of 90° during the movement controlled with the linear encoder, and the need to keep the tether taut to avoid contamination of the results. Subjects performed a standardized warm-up on a cycloergometer (five minutes at 95 W), followed by two sets of four repetitions of bilateral squats with and without the pielaser in a flywheel at submaximal effort. Finally, subjects performed two sets of six repetitions at maximal voluntary effort, the first set on a stable surface, the second using an unstable surface. Experimental setup can be viewed in Fig. 1. To create an unstable surface, subjects stood upon two Pielasters (Biolaster, Guipúzcoa, Spain), which are independent rigid elliptical spheroid platforms. This method of producing instability was chosen because it allows for the placement of a pulley on the ground between the independent spheroid platforms and has previously been used in previous flywheel resistance training literature (Vázquez-Guerrero et al., 2016). A rest interval of one minute was provided between sets. Subjects held their arms against their body while squatting on the inertial flywheel device under both conditions. Maximal effort was produced in the concentric phase. The raw force signals for all repetitions of each set under stable and unstable surfaces were kept for analysis. During all squats, subjects were required to wear an adjustable harness equipped with a carabineer. The subjects placed their feet at hip width on either side of the pulley located on the ground. This position was marked on the floor and was maintained across sets. The tether of the inertial flywheel device was then tied to the harness through the strain gauge using carabineers. Finally, the tension of the tether was adjusted so that both legs could be extended. The rotation system was initiated by winding the tether until reaching 90° of knee flexion, determined by visual inspection. Thereafter, the subject initiated the movement, progressively increasing the velocity until the third repetition from which the velocity was near maximal. After that, the subject performed six repetitions at maximal concentric effort. These six repetitions were computed to calculate the SampEn of the force time series, with entropy being used to quantify the amount of regularity and the unpredictability of force fluctuations in large sets of time-series data (Richman & Moorman, 2000). Each repetition involved squatting to a knee angle of approximately 90°, with this being visually monitored throughout the study by the primary investigator. Verbal encouragement was provided to ensure maximal effort.
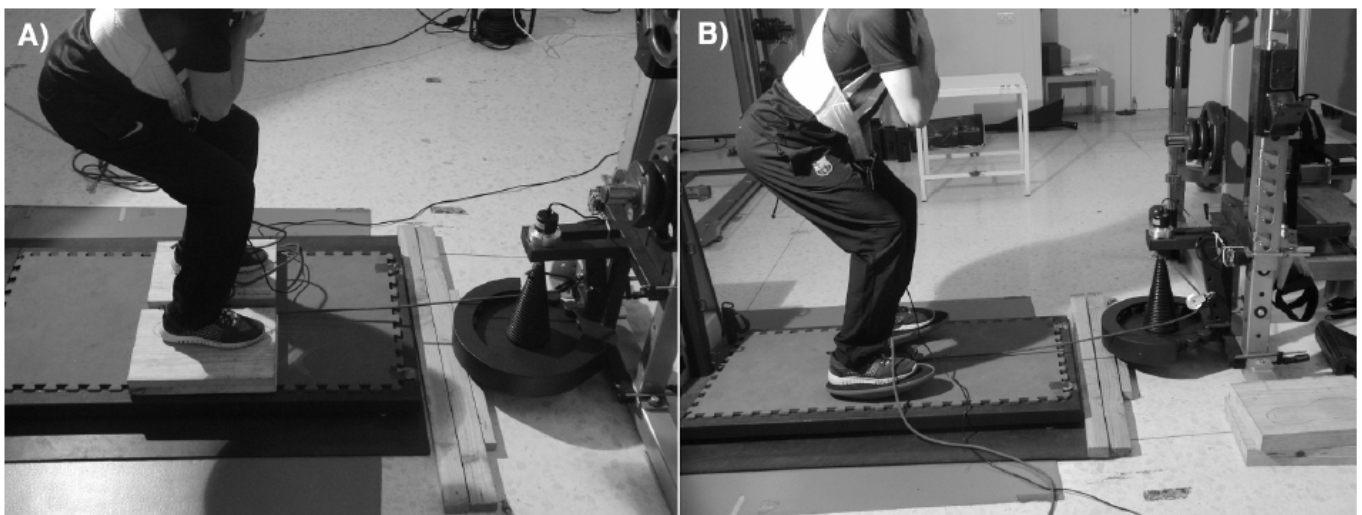

Fig. 1. Experimental setup. (A) Stable surface and (B) unstable surface.

4.4 Statistical analysis

The results were described using proportions for categorical variables, and mean and standard deviations for continuous variables. The different response variables (Force, SampEn, Velocity, Time and Displacement) were analysed using a general linear mixed model, considering condition (stable and unstable) and sets (1 to 6), as well as their interactions, as fixed factors and subject (participant) as a random factor. All statistically non-significant

interactions were removed from the model. Post-hoc multiple comparisons between conditions were carried out with Bonferroni correction. The relationships between SampEn and Force were evaluated using the Pearson correlation coefficient.

The statistical analyses were performed using PASW® Statistics v21.0 (formerly SPSS Statistics) (SPSS, Inc., Chicago, IL, USA) and SAS v.9.3 (SAS institute Inc., Cary, NC, USA). Statistically significant differences were established at $P < 0.05$.

5   Results

Mean force, velocity, time, displacement, and SampEn results are presented in Table 1. The results showed no significant differences for any of the dependent variables between stable and unstable conditions. Additionally, SampEn (chi-squared=0.048 P=0.827) showed no significant differences between conditions.

Force$_{mean}$ and SampEn presented a small correlation (r=0.184; p < 0.01). Fig. 2 shows the correlation coefficient between mean force and SampEn under stable and unstable conditions.

Fig. 3 shows SampEn over the six sets performing squats under stable and unstable conditions (chi-squared=3.420; p=0.527).

	Squat on rotational resistance device			
Mechanical outputs	Stable	Unstable	Chi-squared	p
<Force> (N)	658.37 ± 156.35	632.43 ± 159.13	1.832	0.176
<Velocity> (m/s)	0.69 ± 0.09	0.70 ± 0.08	0.246	0.620
Time (s)	1.36 ± 0.08	1.37 ± 0.07	0.717	0.397
Displacement (m)	0.93 ± 0.06	0.94 ± 0.07	0.518	0.472
SampEn	0.227± 0.04	0.228± 0.05	0.048	0.827

Table 1 Mechanical outputs performing squats on the inertial flywheel device under stable and unstable conditions (n=20).
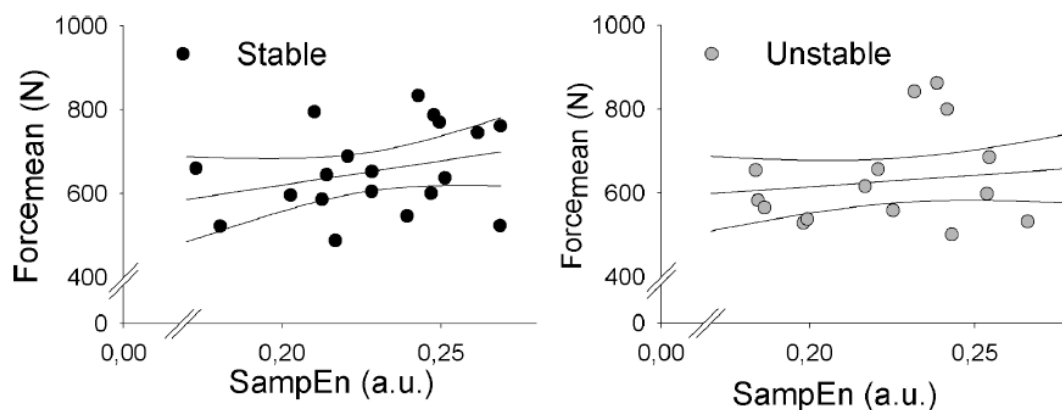

Fig. 2. Correlation between Force$_{mean}$ production in the inertial flywheel device and Sample entropy (SampEn) under stable and unstable conditions (n=20). Lines represent average and standard deviations.
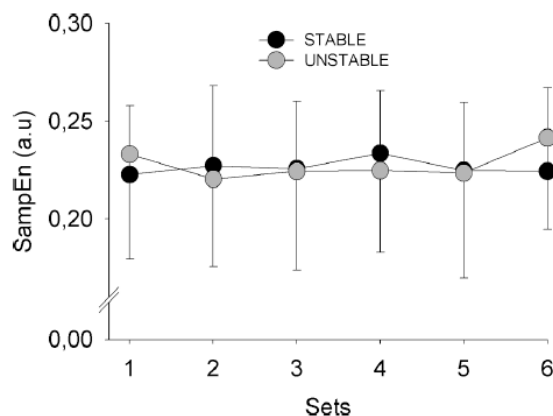
Fig. 3. Sample entropy (SampEn) over the six sets performing squats under stable and unstable conditions (chi-squared=3.420; p=0.527).

6   Discussion

The current study aimed to identify the changes of temporal structure of force variability using nonlinear techniques during the flywheel bilateral squat using stable versus unstable surfaces. In contrast to the study hypothesises, it was found that unstable squat exercises performed with an inertial flywheel device did not result in higher SampEn compared with a stable condition. However, our hypothesis did agree that SampEn did not demonstrate a strong relationship with increases in force production and that SampEn did not change during the exercise. These findings suggest the addition of unstable surfaces during the flywheel squat do not cause significant changes in kinetic and kinematic variables. Furthermore, across six sets of six repetitions, unstable surfaces do not cause substantial changes in force variability.

Results from this study show few differences in entropy when subjects performed squats with an inertial flywheel device under stable and unstable conditions. Additionally, it is important to note that forcemean and the total length of the time series were similar under both conditions (stable and unstable), which corroborates with previous research (Moras & Vázquez-Guerrero, 2015). It is speculated that postural reactions and anticipatory postural adjustments were completed by the subjects balancing on the Pielaster to offset the perturbation around the ankle. This demonstrates the ability of individuals to maintain force production despite changes in stability during exercise.

A small correlation between Forcemean and SampEn (R^2=0.033) was found. The initial development of force variability models (Meyer, Smith, & Wright, 1982) relied on the basic assumption that there is a linear and proportional relation between the magnitudes of force generated and force variability. Later, this linear and proportional relation was found to be untenable across any extended range of response conditions (Hancock & Newell, 1985). Most studies have been carried out using isometric tasks, but assessments during commonly used resistance training movements responses in which a change of displacement occurs have received limited attention. To date, assessment of variability has been expressed as a standard statistical measure such as the standard deviation or the signal-to-noise-ratio (coefficient of variation), and have not been analysed from a nonlinear perspective. It seems important to note that the standard deviation, which provides an index of the degree of deviation from a point in a distribution of scores, captures only the magnitude of fluctuation in a system. The present study extends the findings to more natural movements such as dynamic squats in which body displacement occurs as a function of time, and analyses the structure of force variability obtained with entropy.

The results of our study also showed a small correlation between Forcemean and SampEn demonstrating similar structures of force variability despite different mean force output. Somehow each subject demonstrated a performance profile, typically known as digital fingerprint that was replicated across both conditions. (Couceiro, Dias, Mendes, & Araujo, 2013). This suggests that temporal series with different magnitudes show similar levels of consistency between different individuals (Slifkin, Vaillancourt, & Newell, 2000). Furthermore, this indicates that

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both structures of force variability and forcemean output as a magnitude should provide relevant information to monitor the training process (Rathleff et al., 2011). This could allow for further analysis of intra- and interpersonal variability of motor behaviour in performance across time points and in different contexts.

Finally, no changes in entropy were found over the course of the series, possibly due to insufficient fatigue and subjects being able to maintain a similar motor unit recruitment with similar firing rates (Troiano et al., 2008). Fatigue is known to not only restrict force producing capacity but also the ability to perform controlled and smooth actions. Therefore, our results suggest that the workload imposed was not sufficient to impair the subjects force or the structure of force variability (Cortes, Onate, & Morrison, 2014). Consequently, the maintenance of force output and entropy values across both conditions suggests an insufficient neuromuscular challenge. This may be important for practitioners when considering changes in force and its application when performing bilateral squats in flywheel device in unstable surface.

Although this study is the first to utilise a nonlinear assessment of force variability in stable and unstable resistance training exercise, it is not without its limitations. First, force was recorded by a strain gauge. While the vertical axis was likely to be the least affected by the perturbation produced by the Pielaster, it should be noted that during flywheel training, force is applied around a rotational shaft that comes from directly below the participant. Consequently, it was not possible to identify forces that were applied through the anterioposterior and mediolateral planes (Oshita & Yano, 2011). Second, the sampling rate of the strain gauge may not be in accordance with the sampling theorem that states that the signal must be sampled at a rate at least twice as high as its highest frequency (Winter, 2009). To the best of the author's knowledge a minimum frequency has not been established for the squat exercise. But, due to the strain gauge sampling only at 100 Hz, there is potentially a small chance for bias to occur. Finally, due to the subjects' lack of experience with the flywheel device, it is not possible to discount the effect of training experience. While familiarization with all equipment did happen prior to testing, it is possible that with greater training experience, discrepancies in kinetic and kinematic outputs and variability may have occurred.

In conclusion, the current study demonstrated that unstable surfaces did not cause greater increases in entropy and changes in kinetic and kinematic outcomes. Additionally, increases in force did not accompany increases in entropy and that this variability did not increase during exercise. These outcomes may have been due to the protocol of six sets of six repetitions not developing enough neuromuscular fatigue to disturb motor unit firing and force application. Consequently, findings from this study suggest that practitioners may be able to employ unstable training with a flywheel device without inducing increases in movement variability and alterations in kinetic and kinematic outputs.

7   Practical applications

The use of unstable surfaces when resistance training is often implemented when resistance training to alter the training stimulus that is applied. However, findings from this study demonstrate that when employing unstable surfaces with a low to moderate number of repetitions (i.e. ≤6), changes in kinetic and kinematic, and movement variability do not occur. This suggests that during relatively low training volumes, athletes are able to mitigate any changes in force production by altering upper body posture. Consequently, when practitioners are aiming to cause greater movement variability when training, increased training volumes or intensity may be required during unstable environments to cause a desired training stimulus.

8   Acknowledgments

9 References

Anderson, K. G., & Behm, D. G. (2004). Maintenance of EMG activity and loss of force output with instability. Journal of Strength and Conditioning Research, 18(3), 637–640.

Behm, D., & Colado, J. C. (2012). The effectiveness of resistance training using unstable surfaces and devices for rehabilitation. International Journal of Sports Physical Therapy, 7(2), 226–241.

Berg, H. E., & Tesch, P. A. (1998). Force and power characteristics of a resistive exercise device for use in space. Acta Astronautica, 42(1–8), 219–230.

Burioka, N., Cornelissen, G., Halberg, F., Kaplan, D. T., Suyama, H., Sako, T., & Shimizu, E. (2003). Approximate entropy of human respiratory movement during eyeclosed waking and different sleep stages. Chest, 123(1), 80–86.

Cavanaugh, J. T., Kochi, N., & Stergiou, N. (2010). Nonlinear analysis of ambulatory activity patterns in community-dwelling older adults. Journals of Gerontology. Series A: Biological Sciences and Medical Sciences, 65(2), 197–203. https://doi.org/10.1093/gerona/glp144.

Christou, E. A. (2005). Visual feedback attenuates force fluctuations induced by a stressor. Medicine & Science in Sports & Exercise, 37(12), 2126–2133.

Christou, E. A., & Carlton, L. G. (2001). Old adults exhibit greater motor output variability than young adults only during rapid discrete isometric contractions. The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 56(12), B524–B532. https://doi.org/10.1093/gerona/56.12.B524.

Cortes, N., Onate, J., & Morrison, S. (2014). Differential effects of fatigue on movement variability. Gait & Posture, 39(3), 888–893. https://doi.org/10.1016/j.gaitpost.2013.11.020.

Couceiro, M. S., Dias, G., Mendes, R., & Araujo, D. (2013). Accuracy of pattern detection methods in the performance of golf putting. Journal of Motor Behavior, 45(1), 37–53. https://doi.org/10.1080/00222895.2012.740100.

Davids, K. W., Button, C., & Bennett, S. J. (2008). Dynamics of skill acquisition: A constraints-led approach. Human Kinetics.

de Hoyo, M., Pozzo, M., Sanudo, B., Carrasco, L., Gonzalo-Skok, O., Dominguez-Cobo, S., & Moran-Camacho, E. (2015). Effects of a 10-week in-season eccentricoverload training program on muscle-injury prevention and performance in junior elite soccer players. International Journal of Sports Physiology and Performance, 10(1), 46–52. https://doi.org/10.1123/ijspp.2013-0547.

Deffeyes, J. E., Harbourne, R. T., Stuberg, W. A., & Stergiou, N. (2011). Approximate entropy used to assess sitting postural sway of infants with developmental delay. Infant Behavior & Development, 34(1), 81–99. https://doi.org/10.1016/j.infbeh.2010.10.001.

Dias, G., Couceiro, M. S., Barreiros, J., Clemente, F. M., Mendes, R., & Martins, F. M. (2014). Distance and slope constraints: Adaptation and variability in golf putting. Motor Control, 18(3), 221–243. https://doi.org/10.1123/mc.2013-0055.

Enoka, R. M., Christou, E. A., Hunter, S. K., Kornatz, K. W., Semmler, J. G., Taylor, A. M., & Tracy, B. L. (2003). Mechanisms that contribute to differences in motor performance between young and old adults. Journal of Electromyography and Kinesiology, 13(1), 1–12. https://doi.org/10.1016/s1050-6411(02)00084-6.

Hancock, P. A., & Newell, K. M. (1985). The movement speed-accuracy relationship in space-time. In H. Heuer, U. Kleinbeck, & K.-. H. Schmidt (Eds.). Motor behavior (pp. 153–188). Berlin Heidelberg: Springer. https://doi.org/10.1007/978-3-642-69749-4_5.

Harris, C. M., & Wolpert, D. M. (1998). Signal-dependent noise determines motor planning. Nature, 394(6695), 780–784.

Kouzaki, M., Shinohara, M., Masani, K., & Fukunaga, T. (2004). Force fluctuations are modulated by alternate muscle activity of knee extensor synergists during lowlevel sustained contraction (Vol. 97). doi: 10.1152/japplphysiol.00418.2004.

Meyer, D. E., Smith, J. E., & Wright, C. E. (1982). Models for the speed and accuracy of aimed movements. Psychological Review, 89(5), 449–482.

Moras, G., & Vázquez-Guerrero, J. (2015). Force production during squats performed with a rotational resistance device under stable versus unstable conditions. Journal of Physical Therapy Science, 27(11), 3401–3406.

Norrbrand, L., Pozzo, M., & Tesch, P. A. (2010). Flywheel resistance training calls for greater eccentric muscle activation than weight training. European Journal of Applied Physiology, 110(5), 997–1005. https://doi.org/10.1007/s00421-010-1575-7.

Oshita, K., & Yano, S. (2011). Asymmetry of force fluctuation during low and moderate intensity isometric knee extensions. Perceptual and Motor Skills, 112(3), 860–870.

Pincus, S. M. (1991). Approximate entropy as a measure of system complexity. Proceedings of the National Academy of Sciences, 88(6), 2297–2301. https://doi.org/10.1073/pnas.88.6.2297.

Pincus, S. M., & Goldberger, A. L. (1994). Physiological time-series analysis: What does regularity quantify? The American Journal of Physiology, 266(4 Pt 2), H1643–H1656.

Rathleff, M. S., Samani, A., Olesen, C. G., Kersting, U. G., & Madeleine, P. (2011). Inverse relationship between the complexity of midfoot kinematics and muscle activation in patients with medial tibial stress syndrome. Journal of Electromyography and Kinesiology, 21(4), 638–644. https://doi.org/10.1016/j.jelekin.2011.03.001.

Rezek, I. A., & Roberts, S. J. (1998). Stochastic complexity measures for physiological signal analysis. IEEE Transactions on Biomedical Engineering, 45(9), 1186–1191. https://doi.org/10.1109/10.709563.

Richman, J. S., & Moorman, J. R. (2000). Physiological time-series analysis using approximate entropy and sample entropy. American Journal of Physiology-Heart and Circulatory Physiology, 278(6), H2039–H2049.

Seely, A. J. E., & Macklem, P. T. (2004). Complex systems and the technology of variability analysis. Critical Care, 8(6), R367.

Silva, P., Duarte, R., Sampaio, J., Aguiar, P., Davids, K., Araújo, D., & Garganta, J. (2014). Field dimension and skill level constrain team tactical behaviours in smallsided and conditioned games in football. Journal of Sports Sciences, 32(20), 1888–1896.

Slater, L. V., & Hart, J. M. (2017). Muscle activation patterns during different squat techniques. Journal of Strength and Conditioning Research, 31(3), 667–676.

Slifkin, A. B., Vaillancourt, D. E., & Newell, K. M. (2000). Intermittency in the control of continuous force production. Journal of Neurophysiology, 84(4), 1708–1718.

Stergiou, N., & Decker, L. M. (2011). Human movement variability, nonlinear dynamics, and pathology: Is there a connection? Human Movement Science, 30(5), 869–888.

Stergiou, N., Harbourne, R. T., & Cavanaugh, J. T. (2006). Optimal movement variability: A new theoretical perspective for neurologic physical therapy. Journal of Neurologic Physical Therapy, 30(3), 120–129.

Tracy, B. L., Maluf, K. S., Stephenson, J. L., Hunter, S. K., & Enoka, R. M. (2005). Variability of motor unit discharge and force fluctuations across a range of muscle forces in older adults. Muscle and Nerve, 32(4), 533–540. https://doi.org/10.1002/mus.20392.

Troiano, A., Naddeo, F., Sosso, E., Camarota, G., Merletti, R., & Mesin, L. (2008). Assessment of force and fatigue in isometric contractions of the upper trapezius muscle by surface EMG signal and perceived exertion scale. Gait and Posture, 28(2), 179–186. https://doi.org/10.1016/j.gaitpost.2008.04.002.

Vázquez-Guerrero, J., & Moras, G. (2015). Cambios en la arquitectura muscular y en la velocidad de ejecución de sentadillas en VersaPulley en condiciones estables e inestables en jugadores junior de baloncesto de élite durante una temporada. Cuadernos de Psicología Del Deporte, 15(3), 243–252.

Vázquez-Guerrero, J., Moras, G., Baeza, J., Rodríguez-Jiménez, S., Vazquez-Guerrero, J., Moras, G., … Rodríguez-Jiménez, S. (2016). Force outputs during squats performed using a rotational inertia device under stable versus unstable conditions with different loads. PLoS ONE, 11(4), e0154346. https://doi.org/10.1371/journal.pone.0154346.

Winter, D. A. (2009). Biomechanics and motor control of human movement. John Wiley & Sons.

Zemková, E. (2017). Instability resistance training for health and performance. Journal of Traditional and Complementary Medicine, 7(2), 245–250.