Effects of task and environmental constraints on axial kinematic synergies during the tennis service in expert players

SHAFIZADEH, Mohsen <http://orcid.org/0000-0002-7524-1058>, BONNER, Stuart, BARNES, Andrew <http://orcid.org/0000-0001-8262-5132> and FRASER, Jonathan

Effects of task and environmental constraints on axial kinematic synergies during the tennis service in expert players

Mohsen Shafizadeh, Stuart Bonner, Andrew Barnes, Jonathan Fraser

Faculty of Health and Wellbeing, Sheffield Hallam University, Sheffield, UK

Running head: constraints and synergies in tennis service

Corresponding author: Mohsen Shafizadeh, Academy of Sport and Physical Activity, Faculty of Health and Wellbeing, Sheffield Hallam University, Sheffield, UK, S10 2BP,

Email: m.shafizadeh@shu.ac.uk; Tel: 00441142252518

Abstract

The aims of this study were to examine the effects of task and environmental constraints on axial synergies and to find an association between synergies and arm acceleration as a performance variable. Participants of this study were 10 expert tennis players (age: 34.4±7.46) who voluntarily took part and executed 60 serves under two different conditions: no-opponent and opponent. An inertial motion unit (IMU) capture system was used to calculate the 3D angular joint motions in the neck, back and lumbar segments. The results of the principal component analysis showed that the redundancy in the axial segments is decomposed into 2 main synergies that are responsible for the loading (backward swing) and firing phase (forward swing). The total variance and loading synergy variance were significantly lower in the topspin service than other service types. The emerged firing synergy was strongly associated with the arm acceleration regardless of service type. In conclusion, the effective strategy to utilise the axial motions in the trunk is through creating functional synergies that have a flexible role based on the type of service and conditions. The topspin service showed less coordination variability relative to other types of service and serving in the opponent condition required participants to change the nature of synergy among the axial segments. These findings support the design of practice that emphasises the importance of more realistic contexts with special attention given to the order of different service types.

Keywords: trunk stabilisation, redundancy, kinematic synergies, acceleration.

Introduction

The ability to configure redundant joint motions in different sports skills and daily tasks is an important control mechanism for human movement. According to dynamical systems theory (Bernstein, 1967), the redundancy or variability in the musculoskeletal system has an important functional role in the acquisition of consistent and accurate performance (Vereijken, 2010). One strategy to control the redundancy at the brain, muscle and joint levels is through creating a synergy (Latash & Anson, 2006). Synergy development is the way in which the system learns how to co-vary (share) its elements effectively to stabilise the performance outcome (Gelfand & Latash, 1998). For example, a tennis service as an interceptive motor skill, requires coordination between the active body parts for a ball-racket contact at the optimal time and place.

A biomechanical principle that plays an important role in producing an effective tennis service is the kinetic chain which is formed through the force generated from the sequential action of the legs, trunk and arms (Elliott, 2006; Myers, Kibler, Lamborn, Smith, English, Jacobs, & Uhl, 2017). The sequential actions in the axial muscles require activation of the hips, trunk and head for different purposes. The axial muscles through multi-directional motion (flexion, lateral bend and rotation) generate angular momentum for powerful strokes (Bahamonde, 2002) and stabilise the lumbar spine to minimise the risk of injuries during the service (Chow, Shim & Lim, 2003).

The formation of axial kinematic synergies during functional movements such as trunk motion in sagittal plane has been exhibited in previous studies (Alexadrov, Frolov & Massion, 1998; Ramos & Stark 1990). By using principal component analysis (PCA), Alexandrov et al. (1998) showed that during trunk flexion, coordination among the lower extremities and trunk was controlled by a single kinematic synergy regardless of condition (forward/backward; slow/fast). This might suggest a fixed kinematic synergy in simple movements that is controlled centrally by feedforward mechanisms and is not affected by task (Massion, Popov, Fabre, Rage, & Gurfinkel, 1997). However, the generalisability of such a simple synergistic unit to more complex actions such as a tennis service is limited due to the distinct stages of the action characterised by different types of muscle contraction. For example, in one classification the service is broadly segmented into 2 phases: eccentric contractions phase followed by concentric contractions phase through use of the stretch-shortening cycle (Elliott, 2006), whereas Kovac and Ellenbecker (2011) introduced 8-stage model that includes 1-start (ball and racket at rest), 2-release (when the ball is released from the non-racket hand), 3-loading (full weight over the lower body), 4-cocking (maximum shoulder rotations with maximum knee flexion), 5-acceleration (to contact with the racket), 6-contact (short racket-ball contact time), 7-deceleration (upper body and lower body deceleration after contact) and 8-finish (the last moment of the service action). The action complexity in service might require different kinematic synergies from the joints motions. One advantage of a synergistic unit among the involved segments in a tennis service is to minimise muscle imbalances caused by an increased reliance on certain body segments (Ellenbecker & Roetert, 2004). Synergic units can determine the power generated through the kinetic chain that is transferred from the lower body to the upper body segments. For example, it has been reported that the synergic unit between the legs and trunk develops 51-55% of the kinetic energy and force transmitted to the hand (Kibler, 1995). However, poor coordination between body segments may affect the transfer of energy up the kinetic chain. According to the constraints-led approach, the emergence of a motor behaviour is constrained by interactions between organismic (personal), environment (e.g. temperature, surface, humidity, crowds and opponents) and task (e.g. speed-accuracy trade-off, simple/complex task and the level of cognitive activity) properties (Newell, 1986; Chow, Davids, Button, & Renshaw, 2016). Task constraints are factors which have been found to influence kinematic and kinetic of the action during a tennis serve. Segmentation of the service movements according to the 8-stage model might not be effective in practice if the task differs. In fact, the kinematic and kinetic parameters among the body segments might be changed according to the type of service performed. A previous study by Chow and colleagues (2003) showed that the abdominal muscles are more active in the topspin serve than the flat and slice serves during the upward racket swing until ball-racket contact. Further, this study showed the magnitude of force and torque in the back and shoulder segments were greater in the topspin serve compared to other service types (Abrams, Harris, Andriacchi, & Safran, 2014), highlighting a potential injury mechanism associated with this type of serve over multiple repetitions (Abrams, Sheets, Andriacchi, & Safran, 2011). In addition, there were not significant differences between service type for back extension, axial rotation and lateral trunk flexion in the advanced tennis players (Chow, Park, & Tillman, 2009). Another potential influential task constraint is service speed. In fact, lumbar loading increases with service speed due to the active segments needing to rotate quicker if the type of service requires more power (Elliott, Fleisig, & Nicholls, 2003).

Body mechanics and kinematic synergies during the serve may also be affected by environmental constraints. A previous study (Shafizadeh, Bonner, Fraser, & Barnes, 2019) showed that the kinematic synergies in the upper-limbs during the service were changed when serving with and without an opponent, a difference that may be attributed to the requirement of performers re-calibrate their action accordingly. This finding further supports the fact that synergies are modifiable and flexible action units that change their roles according to the situations (Dickinson, Farley, Full, Koehl, Kram, & Lehman, 2000). Designing practice settings that can simulate the interactions of the body, environment and task could facilitate acquisition and refinement of motor skills. According to representative learning design (Pinder, Davids, Renshaw, & Araújo, 2011), the functionality of motor skills depends on the similarity between the practice context and the real context (Araújo, Davids, & Hristovski, 2006). The functionality of an action is determined by how the arrangement of constraints (e.g. environment or task) represents the behavioural setting in which the action is intended to apply (Hammond & Stewart, 2001). Identification of functional kinematic synergistic units that control the axial segments during the service could be informative for coaches and practitioners to design conditioning programmes for improving postural stability, muscle balance and coordination.

To understand the nature of adaptations in axial kinematic synergies, the primary aim of this study was to examine the effects of task and environment constraints on the axial kinematic synergies during the tennis service. We hypothesised that the emergent axial kinematic synergies during service are not separated from the racket-arm acceleration because they are part of a same kinetic chain, and any adjustments in the nature of the task and environment could re-shape the relationship between the axial synergies and the main effector (racket-arm). Thus, the secondary aim of this study was to examine the association between the racket-arm acceleration and emergent kinematic synergies.

Methods

Participants

Ten (9 males and 1 female) expert tennis players (age: 34.4±7.46; height: 179.85±8.35; body mass: 81.2±13.27) volunteered to take part in this study. From the sample, 6 participants were right-handed. Their current ratings, according to the British Lawn Tennis Association ranged between 1.1 and 7.2. All participants were free from injury at the time of testing. Institutional ethical approval was obtained for all stages of the study, and the participants gave informed consent form before taking part.

Measurements

An IMU motion capture system (ISen, STT systems Co, Spain) that integrates 3D data from accelerometers, gyroscopes and magnetometers was used to measure joint angular displacements. The system has previously been used to study the tennis service when analysing upper-limb angular displacements (Shafizadeh et al., 2019). IMU motion capture systems (APDM) have been validated in previous studies and demonstrated good reliability and accuracy in measuring the head and trunk motions during standing, walking, tandem walking and turning (Parrington, Jeho, Fion, Pearson, El-Gohary, & King., 2018; Bergamini, Melis, Lentola, & Camomilla, 2013). To reduce any measurement errors associated with sensor placement, the same experienced researcher applied the sensors to each participant to ensure correct and consistent placement.

The biomechanical model used in this study included joint angular motions that were calculated from adjacent sensors placed at the neck, back and lumbar areas, using 9 degrees of freedom: flexion/extension, lateral flexion, rotation. The wearable sensors were attached to the head, upper back (T1), lower back (L1) and sacrum using elastic straps so that the X, Y and Z axes were oriented in the sagittal, frontal and transverse planes, respectively. An extra sensor was used on the middle point of humerus (racket arm) for event detection (start/finish) during the service action. All sensors were synchronised and a digital high definition webcam (25Hz) was used to capture the background information to verify tennis service events. The camera was placed behind the court at a distance of 4 meters from the participant.

Procedure

Participants performed a 10 minute general dynamic warm-up followed by a series of tennis specific drills normally seen in a tennis warm-up. Participants were asked to perform a series of serves from behind the baseline in two different conditions: no-opponent (control) and with an opponent (opponent). In the control condition, there was no opponent and participants were asked to serve to an empty court. In the opponent condition, participants served against a similar standard opponent who stood in a common service returning area, one meter behind the baseline. The order of conditions was counterbalanced so that half the participants started the experiment with the control condition and the rest with the opponent condition. The participants completed 30 successful serves (landing in the service box) per condition. There was a 20 seconds rest between trials and 5 minutes rests between conditions to prevent any fatigue effects. To assess the effect of the task constraint on the service mechanics, the participants were requested to randomly change the type of service, but equally, use all of them within each condition. They performed 10 trials for each type of service including slice, topspin and flat in the control and the same amount of serves in the opponent conditions.

Data analysis

Raw segment motions were exported and smoothed in Matlab (Matlab, 2015a, The Mathworks) using a Butterworth 2nd order low pass (10Hz cut-off frequency) filter before, joint angular motions were calculated. The tennis service events were selected according to the 8-stage model proposed by Kovac and Ellenbecker (2011). For the purposes of this study, the start of the action was defined between the shoulder abduction of the racket-arm (the beginning of the release stage) and final moment of the shoulder adduction in the racket-arm (the end of the action following the racket-leg landing). These key points which defined the start and end of the service action were identified using video footage of individual serves and the manual digitisation of the upper-arm sensor graph in Matlab. Due to differences in service duration between trials and participants, all trials were interpolated as a percentage of service time (0-100%). The normalised trials for each individual joint angle were averaged for each participant across 10 trials for each service type and condition.

A PCA was used to quantify the axial kinematic synergies in the tennis service. The aim of this method is to reduce the number of redundant freedoms and convert them into functional units (O'Donoghue, 2008; Witte, Ganter, Baumgart, & Peham, 2010). The orthogonal varimax rotation was used to calculate the total variance and the principal components (PCs) during the entire service. In order to avoid changes in the PC results caused by different ranges of motion of different joints, the joint angles were standardized so they had zero mean and unit variance. Then, the principal component (PC) load vectors were allocated to each time series point. A joint motion (variable) was included in the predictive model if its correlation with the extracted PC was above 0.50 (Deluzio, Harriosn, Coffey, Caldwell, 2014; Jackson, 1993).

The PCA method in this study was used on the mean joints angles. The mean joints angles of each participant were averaged for each service type and condition and the new PCA was calculated from this mean joint matrix; 101 × 9 [service point percentage × joint motion]. A 2 (condition) × 3 (service type) repeated-measures analysis of variance (ANOVA) was used to test the effect of service types and conditions on the total variance and individual variance (PCs). If significant, a Bonferroni post-hoc test was used as a follow-up test.

Cross-correlation functions (CCF) were used to assess the association between racket-arm acceleration and racket-arm abduction, and between racket-arm acceleration and the emerged PCs.

Results

Kinematic Synergies function

The results of the PCA analysis showed that multi-joint axial motions determine more than 80% of the common variance of the tennis service (see Table 1). The results of the PCA showed that the axial motions in all conditions created 2 main kinematic synergies that were responsible for service control before the racket-ball contact (loading synergy) and during and after the racket-ball contact (firing synergy). The results of the ANOVA showed a main effect of service type on total variance ($F_{2,18}$= 3.1, p<0.05) and PC_1 variance ($F_{2,18}$= 7.06, p<0.05). The main effect of condition and the interaction between service type and condition were not significant (p>0.05). Bonferroni post-hoc tests showed that the topspin serve had significantly lower total variance (slice: 85.35±1.8, topspin: 80.65±3.03, flat: 85.4±2.45) and PC_1 variance compared to other types of service (slice: 55.6±3.58, topspin: 48±3.31, flat: 55.8±3.89).

[Table 1 near here]

Kinematic Synergies configuration

By inspection of Figures 1 and 2 and Table 1, it is evident that the synergy configurations have more consistency in the opponent condition compared to the control condition in all types of service. In other words, the axial movements that make up PC_1 in the opponent condition actively contribute during and after the ball-racket contact, mainly requiring axial motions in transverse (rotation) and frontal (lateral flexion) planes to increase the strike power. On the other hand, the PC_2 is mainly composed of axial motions in the sagittal plane (flexion/extension) for the loading phase of service in the opponent condition. The slice serve in the control condition had the highest level of axial contribution (8 DoF) relative to other types of service in PC_1, with neck flexion a common movement pattern observed in all service types and conditions in PC_2. The eigenvectors results (see Table 1) showed that all axial motions are used in the service action (r>0.50).

[Figure 1 near here]

[Figure 2 near here]

Association between kinematic synergies and arm acceleration

The results of CCF showed a significant correlation between arm motion and arm acceleration in all service conditions. More specifically, the correlation was highest with lag

(0) in the control-slice (CCF=0.97, $p<0.05$), opponent-slice (CCF=0.95, $p<0.05$), opponent-topspin (CCF=0.97, $p<0.05$) and opponent-flat (CCF=0.98, $p<0.05$). In the other conditions, the highest correlation was observed in the lag (-4) in control-topspin (CCF=0.85, $p<0.05$) and control-flat (CCF=0.86, $p<0.05$). These results demonstrated strong coupling between racket-arm motion and acceleration in different types of service (see Figure 2).

The results of CCF showed significant inverse correlations between arm acceleration and PC_1 in the control condition (slice: -0.83, $p<0.05$; topspin: -0.68, $p<0.05$; flat: -0.91, $p<0.05$) and significant correlations in the opponent condition (slice: 0.52, $p<0.05$; topspin: 0.48, $p<0.05$; flat: 0.51, $p<0.05$). The correlations between arm acceleration and PC_2 were significant only for the slice and topspin serves in the control condition (slice: -0.36, $p<0.05$; topspin: 0.61, $p<0.05$; flat: 0.02, $p>0.05$) and there were significant inverse correlations with all types of service in the opponent condition (slice: -0.74, $p<0.05$; topspin: -0.78, $p<0.05$; flat: -0.75, $p<0.05$). The results demonstrated that PC_1 is an acceleration-dependent synergy in the opponent condition but not in the control condition. Finally, The PC_2 was found not to be an acceleration-dependent synergy in the opponent condition, too.

Discussion

This study examined the effects of task and environment constraints on the axial kinematic synergies during the tennis service. The findings showed that trunk movements are coordinated by 2 main synergies and the functions of synergies were only affected by task constraints. The findings showed that the multi-joint movements in the trunk during the tennis service are controlled by two main kinematic synergies that have different functional roles: one for loading before the racket-ball contact (PC_1 in the control and PC_2 in the opponent) and another for increasing the power (firing) and acceleration during and after the racket-ball contact (PC_2 in the control and PC_1 in the opponent).

Kovac and Ellenbecker (2011) suggested an 8-stage model in the execution of the tennis service, but the findings of the current study showed that the functionality of axial joint movements could be better explained by a 2-stage model based on the stretch-shortening cycle (Elliott, 2006). In other words, the loading synergy before the ball-racket contact is more active for the backward swing and loading of the muscles to prepare for a powerful stroke. This phase of trunk movement requires eccentric contractions (Elliott, 2006). On the other hand, the kinematic synergy for firing contributes in the concentric shortening phase of the service (during and after the ball-racket contact) to accelerate the racket head and generate maximum racket and ball velocity. Results revealed that the functions of kinematic synergies were only affected by task constraints. The total variance and variance in the "loading synergy" were lower in the topspin serve than other serves. If the axial joints do not work as a unit, the need for more work in individual segments is increased. Thus, the low amount of variance in the topspin serve could place the posture in a more unstable condition specifically in the first phase of the serve. However, this might be a compensatory strategy during topspin serve to meet the requirements of the task. The synergistic unit in the motor system provides a capability for an individual to achieve a task goal in many different ways (Latash, Scholz, & Schoner, 2002). In addition, it adds functional variability in the movement system which is important for preventing injury due to the repetitive execution of a skill (van Emmerik & van Wegen, 2000). Previous research has demonstrated that tennis players generate more force and torque (Abrams, et al., 2014) and activate the abdominal muscles more in the topspin serve than other types of serve (Chow, et al., 2003), potentially increasing the chance of injuries in the back and lower back regions (Abrams, et al., 2011).

Another finding of this study was the effect of environmental constraints on the composition (configuration) of emerged synergies that was measured by eigenvectors in the PCA method. When manipulating the environmental constraints, results showed that the kinematic synergies configurations had more consistency in the opponent condition than the control condition. For example, the movements that made up PC_1 require axial motions in the transverse (rotation) and frontal (lateral flexion) planes, whereas the PC_2 was formed by movements in the sagittal plane (flexion/extension) in the opponent condition regardless of the type of service. The dependency to the environmental condition indicated that the axial movements like other movement patterns (Shafizadeh, et al., 2019; Kim, Kwon, Yenuga, & Kwon, 2010) are adaptable to the situation. This finding may suggest that the movement coordination is facilitated more under real world contexts during practice sessions (e.g. competitive situation). According to representative learning design (Pinder, et al, 2011), the generalisation of motor behaviours depends on the similarity between the practice and the real world context (Araújo, et al, 2006), and the action functionality is determined by how the environment or task constraints represent the target setting in which the action is intended to apply (Hammond & Stewart, 2001).

A secondary aim of this study was to explore the association between the racket-arm acceleration and axial kinematic synergies. We found that the racket arm motion is strongly associated with the arm acceleration, and could be considered an integral part of the kinetic chain that is closely associated with axial joint synergies. Furthermore, the findings of the current study showed that the "firing synergy" is an acceleration-dependent synergy in the opponent condition, whereas the "loading synergy" is not. As elements of the same kinetic chain, the arm acceleration and "firing synergy" work together to transmit the force from the lower body to the racket-arm for powerful strokes.

The findings of this study have some important implications for coaches and strength and conditioning practitioners. Firstly, the segmentation of the service movement pattern according to the 8-stage model is not applicable for axial stability. The 2-synergic model, one for loading and another for firing, is a more effective approach to support the design of postural stability exercises due to the use of different types of muscle contraction in different axes of motion. Strength and conditioning coaches should seek to integrate the 2-synergic model with other training modalities (e.g. resistance bands, medicine balls and modified rackets) to make the service more functional in terms of joint configurations. The 2-synergic model suggests training tasks that simulate the service action as part of a conditioning programme rather than isolated from the real nature of the task could be more representative of competition. Secondly, the findings that kinematic synergy configurations are affected by environmental constraints and are more consistent in the opponent condition could support the application of representative learning design in the coaching of the tennis serve. Instead of the execution of the service to an empty court, the practice session could be enriched through adding a real opponent (practice partner or the coach). Lastly, the current findings showed that the topspin serve utilised less total variance specifically in the back swing phase (loading synergy). This might expose the trunk in an unstable position because of less movement variability in the axial segments. This might further increase the need for more compensation in other segments such as the lower extremities. The accumulation of such compensatory movements over time and specifically in young players might lead to overuse injuries and lower back pain. Thus, service should be practised in a random order and so that the type of service is changed in successive attempts with more rest time between attempts. One limitation of this study is a lack of assessment of the lower extremities that have a significant role in the kinetic chain during a serve. Future studies could use a complex biomechanical model in which the axial segments are assessed along with lower extremities during the service. In addition, whether service speed could result in different or similar axial kinematic synergies is unknown as we did not measure it in this study.

In conclusion, the results of this study showed that the movements of axial joints during the tennis service are coordinated as kinematic synergies that are closely synchronised with backward swing (loading) and forward swing (firing) phases. Because the configurations of synergies were affected by the environment, designing the service practice tasks using an opponent could produce more consistent coordination pattern among the active body parts.

Conflict of interest statement:

The authors report no declarations of interest.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Abrams, G.D., Harris, A.H.S., Andriacchi, T.P., & Safran, M.R. (2014). Biomechanical analysis of three tennis serve types using a markeless system. *British Journal of Sports Medicine 4*, 8339–8342.

Abrams, G.D., Sheets, A.L., Andriacchi, T.P., & Safran, M.R. (2011). Review of tennis serve motion analysis and the biomechanics of three serve types with implications for injury. *Sports Biomechanics, 10,* 378-390.

Alexandrov, A., Frolov, A., & Massion, J. (1998). Axial synergies during human upper trunk bending. *Experimental Brain Research, 118,* 210-220.

Araújo, D., Davids, K., & Hristovski, R. (2006). The ecological dynamics of decision making in sport. *Psychology of Sport and Exercise, 7,* 653–676.

Bahamonde, R. (2002). Changes in angular momentum during the tennis serve. *Journal of Sports Sciences, 18,* 579–592.

Bergamini, E., Melis, M., Lentola, A., & Camomilla, V. (2013). *Estimate of trunk inclinations in fast movements by using inertial sensors*. Paper presented in 31 International Conference on Biomechanics in Sports, Taiwan, 7-11 July.

Bernstein, N. (1967). *The coordination and regulation of movements*. London: Pergamon Press.

Chow, J.-Y., Davids, K., Button, C. & Renshaw, I. (2016). *Nonlinear Pedagogy in Skill Acquisition: An Introduction*. Routledge: London.

Chow, J., Shim, J.h., & Lim, Y.t. (2003). Lower trunk muscle activity during the tennis serve. *Journal of Science and Medicine in Sport, 6,* 512–518.

Chow, J. W., Park, S. A., & Tillman, M. D. (2009). Lower trunk kinematics and muscle activity during different types of tennis serves. *Sports Medicine Arthroscopy Rehabilitaion Therapy and Technology, 1,* 24.

Deluzio, K.J., Harriosn, A.J., Coffey, N., & Caldwell, G.E. (2014) Analysis of biomechanical waveform data. In G.E. Roberston, G.E. Caldwell, J. Hamill, G. Kamen, S.N. Whittlesey (Eds.), *Research methods in biomechanics,* 2nd edition (317-338). IL: Human Kinetics.

Dickinson, M., Farley, C., Full, R. J., Koehl, M.A., Kram, R., Lehman, S. (2000). How animals move: An integrative view. *Science, 88,*100-106.

Ellenbecker, T. & Roetert, P. (2004). An isokinetic profile of the trunk rotation strength in elite tennis players. *Medicine and Science in Sport and Exercise, 36*, 1959–1963.

Elliott, B. (2006). Biomechanics and tennis. *British Journal of Sports Medicine, 40,* 392-396.

Elliott, B., Fleisig, G., Nicholls, R. (2003). Technique effects on upper limb loading in the tennis serve. *Journal of Science and Medicine in Sport, 6*, 76–87.

Gelfand, I.M., & Latash, M.L. (1998). On the problem of adequate language in motor control. *Motor Control, 2,* 306-313.

Hammond, K.R., & Stewart, T.R. (2001). *The Essential Brunswik: Beginnings, Explications, Applications*. New York: Oxford University Press.

Jackson, D. A. (1993). Stopping rules in principal component analysis: A comparison of heuristical and statistical approaches. *Ecology, 74*, 2204-2214.

Kibler, W. B. (1995). Biomechanical analysis of the shoulder during tennis activities. *Clinical Sports Medicine*, *14*, 79-85.

Kim, J.W., Kwon, M.S., Yenuga, S.S., & Kwon, Y.H. (2010). The effects of target distance on pivot hip, trunk, pelvis, and kicking leg kinematics in Taekwondo roundhouse kicks. *Sports Biomechanics*, *9*, 98-114.

Kovacs, M., & Ellenbecker, T. (2011). An 8-stage model for evaluating the tennis serve: Implications for performance enhancement and injury prevention. *Sports Health: A Multidisciplinary Approach, 3,* 504-513.

Latash, M.L., Scholz, J.P., & Schöner, G. (2007). Toward a new theory of motor synergies. *Motor Control*, *11*,276-308.

Latash, M.L., & Anson, J.G. (2006). Synergies in health and disease: relations to adaptive changes in motor coordination. *Physical Therapy, 86,* 1151-1160.

Latash, M.L., Scholz, J.F., & Schoner, G. (2002). Motor control strategies revealed in the structure of motor variability. *Exercise and Sport Science Review, 30, 26-31*.

Massion, J., Popov, K., Fabre, J-C., Rage, P., & Gurfinkel, V. (1997). Is the erect posture in microgravity based on the control of trunk orientation or center of mass position? *Experimental Brain Research, 114*, 384-389.

Myers, N., Kibler, B., Lamborn, L., Smith, B.J., English, T., Jacobs, C., & Uhl, T.L. (2017). Reliability and validity of a biomechanical based analysis method for the tennis serve. *International Journal of Sport Physical Therapy 12*, 437-449.

Newell, K.M. (1986). Constraints on the development of coordination. In M.G. Wade & H.T.A. Whiting (Eds.), *Motor development in children: Aspects of coordination and control* (pp.341-360). Dordrecht, Nethrland: Martinus Nijhoff.

O'Donoghue, P. (2008). Principal components analysis in the selection of key performance indicators in sport. *International Journal of Performance Analysis in Sport, 8*, 145-155.

Parrington, L., Jeho, D. L., Fion, P.C., Pearson, S., El-Gohary, M., & King, L. A. (2018). Validation of inertial sensor algorithm to quantify head and trunk movement in healthy young adults and in individual with mild traumatic brain injuries. *Sensors, 18*, 4501-4510.

Pinder, R., Davids, K., Renshaw, I. & Araújo, D. (2011). Manipulating informational constraints shapes movement reorganization in interceptive actions. *Attention, Perception & Psychophysics 73,*1242-1254.

Pinder, R. A., Renshaw, I. and Davids, K. (2009) Information–movement coupling in developing cricketers under changing ecological practice constraints. *Human Movement Science, 28*, 468-479.

Ramos, C.F., & Stark, L.W. (1990). Postural maintenance during fast forward bending: a model simulation experiment determining the reduced trajectory. *Experimental Brain Research, 82*, 651-657.

Shafizadeh, M., Bonner, S., Fraser, J., & Barnes, A. (2019). Effect of environmental constraints on multi-segment coordination patterns during the tennis service in expert performers, *Journal of Sports Sciences*, *37*, 1011-1020.

van Emmerik, R. E. A. & van Wegen, E. E. H. (2000). On variability and stability in human movement. *Journal of Applied Biomechanics, 16, 394-406.*

Vereijken, B. (2010). The complexity of childhood development: variability in perspective. *Physical Therapy, 90,*1850-1859.

Witte, K., Ganter, N., Baumgart, C., & Peham, C. (2010). Applying a principal component analysis to movement coordination in sport. *Mathematical and Computer Modelling of Dynamical Systems, 16*, 477-488.

Table 1- The correlation coefficient (eigenvectors) between movements and synergies in different conditions.

Service Type/Condition	**Synergy**	
Control	PC1: Loading (58%)	PC2: Firing (28%)
Slice	Lumbar Lateral Flexion(-0.97)	Neck Flexion(0.88)
	Neck Rotation(-0.97)	
	Neck Lateral Flexion(0.96)	
	Lumbar Flexion(0.81)	
	Back Flexion(0.80)	
	Back Rotation(-0.78)	
	Lumbar Rotation(0.73)	
	Back Lateral Flexion(0.66)	
	PC1(47%)	PC2(35%)
Topspin	Lumbar Flexion(0.95)	Lumbar Rotation(0.85)
	Back Flexion(0.80)	Neck Flexion(0.83)
	Back Rotation(-0.80)	Back Lateral Flexion(-0.73)
	Neck Rotation(-0.75)	
	Lumbar Lateral Flexion(-0.74)	
	Neck Lateral Flexion(0.72)	
	PC1(56%)	PC2(31%)
Flat	Neck Lateral Flexion(0.99)	Neck Flexion(0.95)
	Lumbar Lateral Flexion(-0.99)	Lumbar Rotation(0.60)
	Neck Rotation(-0.97)	
	Back Rotation(-0.88)	
	Back Flexion(0.73)	
	Lumbar Flexion(0.72)	
	Back Lateral Flexion(0.68)	
Opponent	PC1: Firing (53%)	PC2: Loading (31%)
Slice	Back Rotation(0.97)	Back Flexion(0.92)
	Lumbar Rotation(-0.93)	Back Lateral Flexion(0.87)
	Neck Rotation(0.91)	Neck Flexion(-0.87)
	Lumbar Lateral Flexion(0.85)	Lumbar Flexion(0.83)
	Neck Lateral Flexion(-0.83)	
	PC1(49%)	PC2(30%)
Topspin	Neck Rotation(0.95)	Back Lateral Flexion(0.87)
	Back Rotation(0.95)	Back Flexion(0.83)
	Lumbar Lateral Flexion(0.90)	Neck Flexion(-0.83)
	Neck Lateral Flexion(-0.89)	Lumbar Flexion(0.76)
	Lumbar Rotation(-0.80)	
	PC1(56%)	PC2(28%)
Flat	Neck Rotation(0.97)	Lumbar Flexion(0.90)
	Back Rotation(0.96)	Back Flexion(0.89)
	Lumbar Lateral Flexion(0.92)	Back Lateral Flexion(0.82)
	Neck Lateral Flexion(-0.86)	Neck Flexion(-0.73)
	Lumbar Rotation(-0.80)	

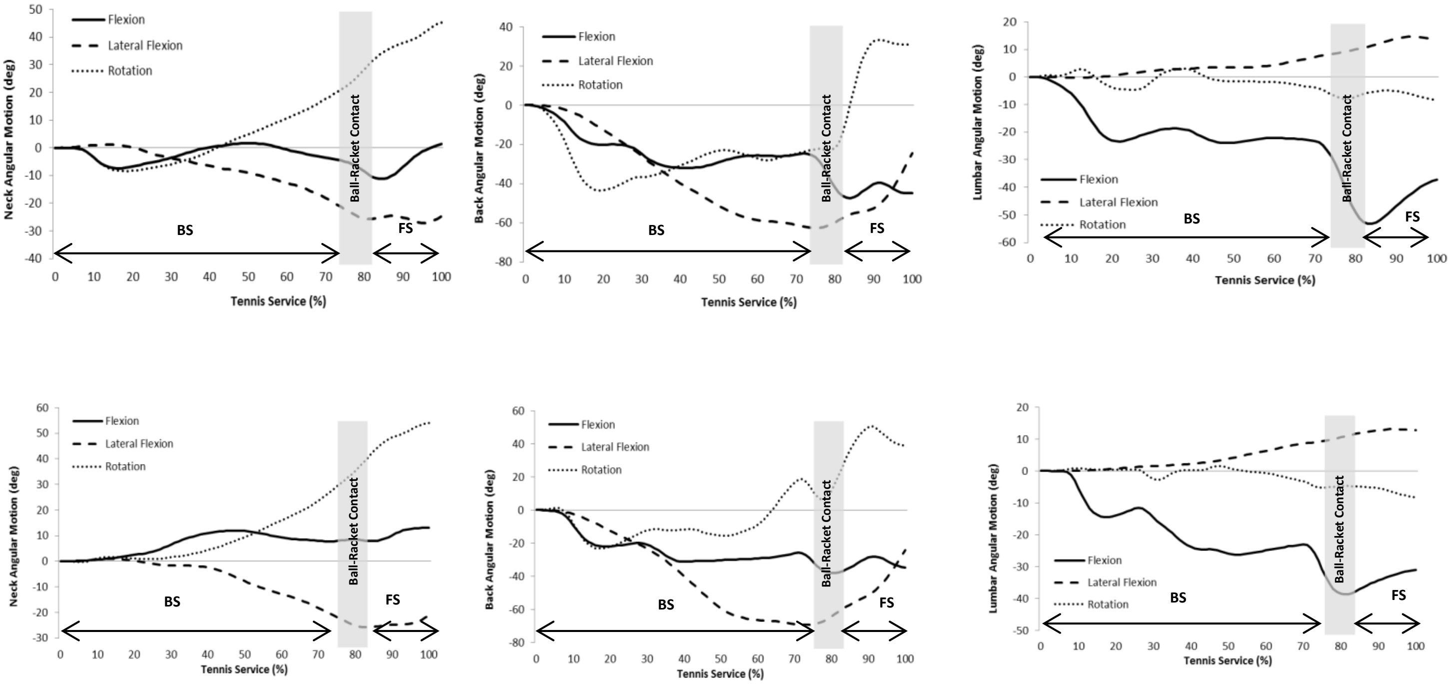

Figure 1- Sample angular motions of different parts of posture during service in the control (top) and the opponent (bottom) conditions. Backswing (BS) and Forward swing (FS).

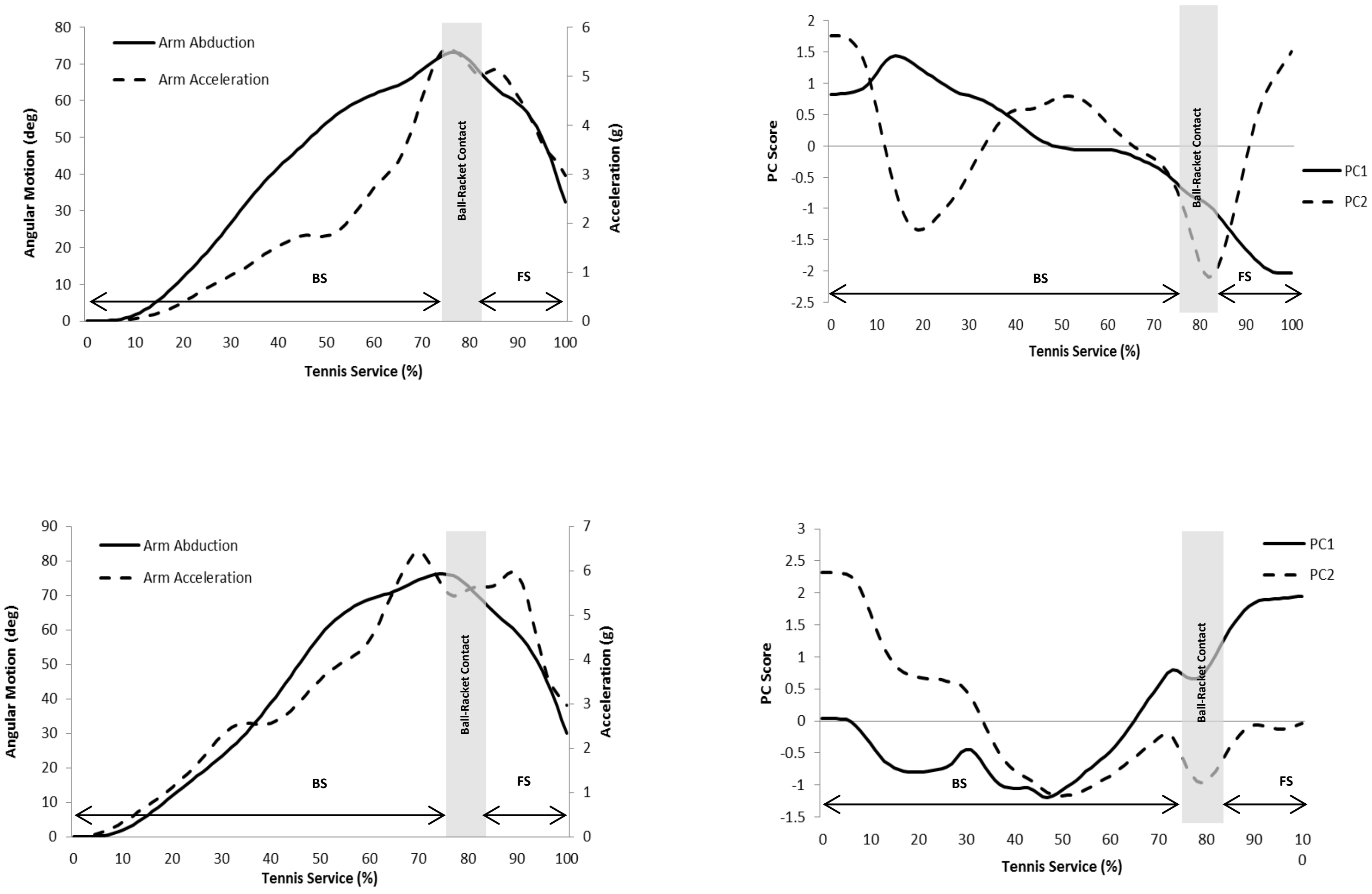

Figure 2- Sample arm motion, arm acceleration and the PC scores during service in the control (top) and the opponent (bottom) conditions.