HOW DOES WHOLE BODY BALANCE CONTROL INTERACT WITH STROKE PERFORMANCE DURING THE TENNIS SERVE?

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The purpose of this study was to investigate whether there is an interaction between mechanisms used to control whole body balance and racket performance. Fourteen experienced tennis players (nine males and five females; age, 21.5±3.9 yr; height, 1.7± 0.1 m; body mass 65.8± 8.1 kg) completed 10 successful tennis serves. Twelve optoelectronic cameras were used to collect kinematic data at 200 Hz (BTS bioengineering, Milan, Italy). Linear regression using 1D Statistical Parametric Mapping was used to identify interactions between the extrapolated centre of mass (XCoM) displacement in the anteroposterior direction and the changes in arms/trunk segment angular momentum, and peak anterior-posterior racket velocity. Overall, no meaningful relationships were found, except for a small time interval during the forward swing phase in which a greater increase in trunk angular momentum was associated with increased maximum racket velocity.

KEYWORDS: balance control, end-effector performance, racket sports.

INTRODUCTION: The serve is the most important stroke for successful performance in tennis (Reid et al., 2011). Many previous biomechanical studies have examined the tennis serve, often focusing on kinematics of upper limbs, trunk, lower limbs and racket (end-effector) (Whiteside et al., 2015; Whiteside et al., 2013; Reid et al., 2008; Reid et al., 2013; Sakurai, 2013; Whiteside et al., 2014). However, end-effector performance is also likely to be affected by simultaneous motions associated to maintaining postural balance, and this to our knowledge has not been previously investigated. It is essential for practitioners to gain a better understanding of the interaction between postural balance control mechanisms and end-effector performance. In training and coaching there is a general awareness of the importance of good postural balance for the successful execution of a tennis serve. However, it remains unclear whether balance training should always be done explicitly in the context of the tennis serve, or whether one can train upper extremity racket control and lower extremity balance control separately. Therefore, gaining a better understanding of how balance and end-effector control may well interact with each other is paramount to supporting developments in training and coaching. The balance mechanisms as described by Hof et al. (2005) are suitable for a dynamic and complex task such as the tennis serve. First, there is the notion of whole body CoM velocity that is taken into account through evaluation of the displacement of the so-called extrapolated CoM (XCoM) relative to the edge of the base of support. Second, there is the incorporation of accelerated segmental motions that influence whole body balance (called counter rotation of segments), which particularly concerns the trunk and upper extremity motions (Hof et al., 2005; Hof et al., 2007). The mechanisms permit the quantitative interaction between motion associated to maintaining postural balance and end-effector performance, but the question remains which balance mechanism will be used and whether that interaction will occur during the tennis serve.

The purpose of this study was to describe the interaction between postural balance control and end-effector performance during the tennis serve. It was hypothesized that if there was an interaction it would be revealed throughout the serving motion, and most strongly in the later phases of the serve.

METHODS: Fourteen right-handed experienced Thai tennis players (nine males and five females; age, 21.50 ± 3.85 years; height, 1.74 ± 0.06 m; body mass 65.79 ± 8.05 kg) participated in this study. This study was approved by the Liverpool John Moores ethics committee (15/SPS/016) and Mahidol university ethics committee (MU-CIRB 2016/013.2201). Sixty eight reflective markers were placed on anatomical landmarks to record segmental motions. Kinematic data were collected with 12 infrared cameras at 200 Hz (BTS bioengineering, Milan, Italy). The markers were applied to 13 segments to allow calibrating and tracking of segmental motion consisting of head, upper arms, forearms (including hands), thorax, pelvis, thighs, shanks, and feet. Prior to performing the task, a static recording was obtained for use in marker definition and model scaling, after which the dynamic trials were recorded. Players used their own rackets to complete the protocol. After a standardised warm-up routine, subjects performed at least 10 maximal effort first serves directed at a 1 x 1 metre target bordering the T of the service box in the deuce court, with a 2-min rest between serves. Ten successful serves including a preparation, propulsion and forward swing phase were analysed. The inverted pendulum mechanism was observed by observing the XCoM in anteroposterior direction. Furthermore, the counter rotation of segments mechanism was observed via the changes in angular momentum of the arms and trunk segment. A 13-segment model was used to calculate the whole-body CoM. The XCoM was calculated using the position of the vertical projection of the CoM added with its velocity multiplied by a factor $\sqrt{l}/g$ (l being leg length and g the gravitational acceleration) (Hof et al., 2005). The angular momenta of the arms (both arms together) and trunk segment relative to the whole-body CoM were separately calculated as the product of their principal moment of inertia (I) and angular velocity in the arms/trunk segment coordinate system (ω). The time derivative was calculated to represent the changes in angular momentum. End-effector performance was quantified through maximum racket velocity, calculated from the peak forward velocity of a marker on the top of the racket. All calculations were implemented in Visual3D software version 6.0 (C-motion, Germantown, MD, USA). Each trial was time normalised to 101 samples (0-100% of cycle time) over the duration of the movement in each phase. Statistical Parametric Mapping (SPM) linear regression was used to examine the within-subject interaction between the XCoM in A/P direction and maximum racket velocity, as well as the interaction between changes in arms and trunk angular momenta and maximum racket forward velocity. The slopes of these relationships were computed at each time t, resulting in β trajectories. These β trajectories were computed for each subject and were subsequently submitted to a population-level one-sample t test, yielding t-statistic curves, or a Statistical Parametric Map. The significance of each SPM{t} was then determined topologically using random field theory (Adler and Taylor, 2007). SPM analyses were implemented using the open-source spm1d code (www.spm1d.org) in Matlab (R2016a, 8.3.0.532, The Mathworks Inc, Natick, MA).

RESULTS AND DISCUSSION: The aim of this study was to investigate whether there is an interaction between postural balance and end-effector performance in the tennis serve of experienced players. The results expressed that there were mostly no systematic relationships between the XCoM or the changes in arms/trunk angular momentum in the A/P direction, and maximum forward racket velocity. However, the only significant relationship observed was between the change in trunk angular momentum and maximum racket velocity in the forward swing phase, just prior to the time at which maximum racket velocity was reached (Figure 1).

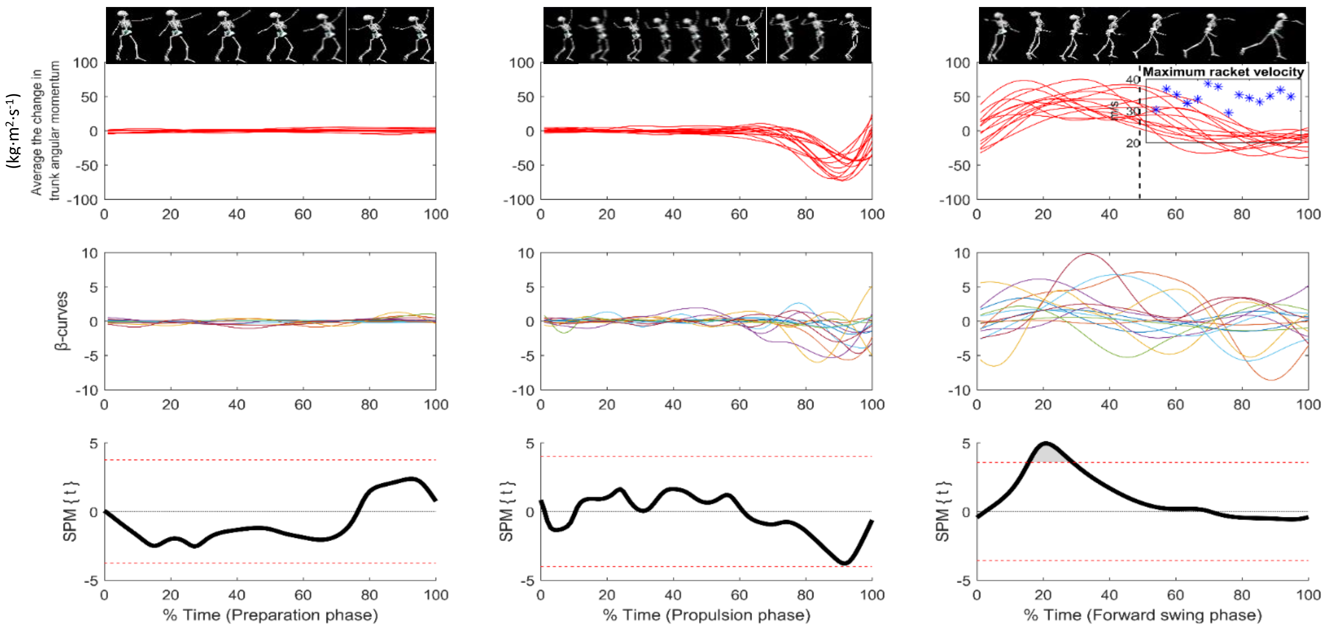

Figure 1: The relationships between changes in trunk angular momentum and maximum racket velocity of 14 participants during the serve

It is worth first reflecting on the possibility that shortly before maximal racket velocity is achieved there may be some interaction with counter rotation of the trunk segment. The kinetic chain theory could be used to explain this through the generation of forces to propel the racket to hit the ball. For example, the coordinated movement starts at the feet pushing against the ground, moving through the trunk and eventually to through the upper extremity to the hand as there is a subsequent increase in velocity of body segments (Abrams et al., 2011). As the last phases have high velocities, it is not unthinkable that the acceleration of the trunk segment determines the end-effector performance. This is also supported by the notion of Crespo and colleagues (1998), stating that trunk and arm rotation work together towards racket velocity. This counter rotation of segments is however also expected to play a role in the maintenance of balance. As the trunk segment moves rapidly from backward to forward during the forward swing phase, the acceleration of this motion is expected to cause an opposite change in angular momentum of the lower extremities, which in turn would generate backwards directed ground reaction forces. Our findings seem to support a relevant interaction between balance control and end-effector performance, yet this would have to be confirmed through further investigation in other serving locations as well as comparing the interaction across the locations to explore that whether this interaction is maintained. Our findings suggest that individual interactions between balance mechanisms which is XCoM location and end-effector outcome were present, but that these were not systematically the same. For example, the β-curves of the interaction between the changes in arms/trunk angular momentum and maximum racket velocity of all participants present little variation in the preparation phase, more variation in the propulsion phase, and the greatest variation in the forward swing phase. Even, the β-curves of these interactions seem to be similar patterns but the β-curve trajectories were not exactly the same. No consistent relationships were observed across all participants. This could be explained due to each player having their own strategy to maintain the balance when executing a maximum racket velocity even when serving to the same serving location. This supports previous suggestions that each individual has a unique ability to maintain their balance depending on what compensatory strategies are required to complete the task successfully (Horak, 2006). It also supports the notion that different athletes perform the same task in different ways, and that there is no single optimal movement pattern to achieve that task for athletes as a whole (Bartlett et al., 2007). Several factors may explain the individuality. First, whilst this study selected a relatively homogenous population (Thai experienced players), there is still a great level of heterogeneity within the population (e.g., gender). Hence, players may have different serving techniques. Second, players are able to adapt differently to the ball toss outcome. The implication of advanced individuality would be that coaches should not just generalise across a population, but that they should provide the attention carefully to their individual players. The practical implementation of the benefit of understanding the interaction between balance mechanisms and end-effector performance, or the lack of such interaction as we found, is for coaches to understand the importance of intrinsic behaviours during the tennis serve that serve multiple purposes. Players need to coordinate the motion of trunk movement and arms swing to maximise performance, but at the same time balance is controlled. Therefore, our findings highlight that the balance control and performance maximisation could be trained separately, or that there is at least no strong evidence that they have to be trained simultaneously. Furthermore, the findings suggest that the interaction between balance control and end-effector performance may well be highly individualised and hence requires an individual training approach.

CONCLUSION: No direct relationship was observed between balance control mechanisms and end-effector behaviour. Experienced players appear to have individualised strategies to maintain their balance during a tennis serve. Therefore, under the constraints of our observations, in experienced players the variation in end-effector behaviour is not directly influenced by behaviours that are associated to maintaining balance. For coaches, this supports the notion that training balance and end-effector control separately remains justified.

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ACKNOWLEDGEMENTS: Thanks Liverpool John Moores University and Mahidol University for the PhD scholarship.