Effect of environmental constraints on multi-segment coordination patterns during the tennis service in expert performers

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Effect of environmental constraints on multi-segment coordination patterns during the tennis service in expert performers

The aims of this study were to examine the effect of different environmental constraints on kinematic multi-segment coordination patterns during the service and its coordination with service time variability. Ten expert tennis players (Age: 34.1±5.3) volunteered to take part in this study. Participants served 30 times in 3 different conditions: control, target and opposition. The order of conditions was counterbalanced between participants. A wireless 3D motion capture system (STT Co, Spain) was used to measure 7 joint motions, with a 17 degrees of freedom biomechanical model created to capture the entire service action. Results of the principal component analysis showed that 4 synergies were created; however, their roles were changed relative to the perception of the environment. The results of repeated-measures analysis of variance did not show any significant difference on total variance and individual principal components between conditions; however, one synergy pattern significantly predicted the service time variability in both control and opposition conditions. In conclusion, the findings demonstrated that expert performers reduce the joint dimensionality by creating functional synergies in different phases of service and adapt the service action according to the perception of the environment.

Keywords: synergies, expertise, tennis service multi-segment action

Subject classification codes: Sports Medicine and Biomechanics

Introduction

The complexity in the control of motor skills is determined by the level of coordination among segments, with the complex interaction of coupled units or multi-segment synergies resulting in an effective performance (Kelso, 1995). The strategy to control the degrees of complexity or dimensionality (low/high) is referred to as "solving the degrees of freedom (DoFs) problem" within motor control theory (Bernstein, 1967; Newell, Broderick, Deutsch, & Slifkin, 2003). According to motor abundance theory (Latash, 2010), the motor system creates different levels of coordinative structure and motor synergies among the segments/joints to solve their dimensionality.

The tennis service is a complex, interceptive motor skill requiring high-levels of inter-limb and intra-limb coordination between different body segments. More specifically, it has been demonstrated that tennis players require an ability to organise the complex segmental sequence of racket-arm movements during groundstrokes using efficient coupling of the upper limbs (Hughes & Bartlett, 2002). Coaches with a greater understanding of specific synergies can utilise this information to provide the most effective training environments to foster players' skill development (Whiteside, Elliott, Lay, & Reid, 2015). In addition, such information may be of use to applied practitioners regarding the strategies employed to prevent the risk of injuries and enhance sports performance (Congeni, McCulloch, & Swanson, 1997).

The effective strategy to control the DoF problem depends on the level of expertise (Williams, Irwin, Kerwin, Hamill, Van Emmerick, Newell, 2015; Federolf, Reid, Gilgien, Haugen, Smith, 2014). Some studies have explored the role of variability in minor (intra-trial variability) and major (inter-trial variability) adaptations. For example, Williams et al. (2015) showed that expert gymnasts had less variability in coordination patterns (shoulder-hip couple) during a longswing exercise, relative to novices. Federolf et al. (2014) suggested a performance signature for experts that accounts for the most variance in the skill. They showed that body inclination was an important feature of alpine skiing that determined over 50% of total variance in elite racers. Further studies have also supported inter-trial variability as an index of adaptation to the situational demands (Wilson, Simpson, Van Emmerik, & Hamill, 2008; Davids, Araújo, Seifert, & Orth, 2015; Orth, ve der Kamp, Memmert, & Savelsbergh, 2017). Wilson et al. (2008) showed that expert triple jumpers had higher coordination variability while less skilled jumpers displayed low coordination variability. Similar results were also reported in other multi-segment skills such as kicking in football (Chow, Davids, Button and Koh, 2008) and shooting in basketball (Rein, Davids and Button, 2009). Therefore, the functionality of movement variability is dependent on level of expertise with expert athletes able to exploit joint dimensionality very differently compared to novices.

Task and environmental constraints have also been suggested to influence segment coordination during the execution of sports specific skills. Kim, Kwon, Yenuga and Kwon (2010) showed that as the target distance for taekwondo fighters increased, the horizontal displacement of the pivot hip towards the target also increased. This finding suggests the existence of biomechanical adaptations in response to the environmental demands of the task. Due to the dynamic interaction between the body and environment, designing practice tasks that can replicate such interactions, plays a key role in supporting the acquisition and refinement of motor skills. According to representative learning design (Pinder, Davids, Renshaw, & Araújo, 2011), the optimal generalisation 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). One aspect of adaptation relates to changes in segment kinematics in response to environmental factors such as opponents and equipment, in both self-paced (Rein et al., 2009; Kim, et al., 2010) and externally-paced motor skills (Stone, Maynard, North, Panchuk, & Davids, 2015a; Panchuk, Davids, Sakadjian, MacMahon, & Parrington 2013; Stone, Maynard, North, Panchuk, & Davids, 2015b). In summary, the adaptations to environmental situations require changing the kinematic configurations of active limbs in both self-paced and externally-paced skills to achieve successful outcomes.

Within the tennis service, developing practice environments which display a degree of similarity between the service practice tasks and game situations are likely to improve the performer-environment interaction (Araújo et al., 2006). The effects of such environmental and informational constraints in externally-paced skills such as return shots from a server have been studied in tennis (Carboch, Suss, & Kocib, 2014). These authors showed that players had a shorter movement initiation and longer back swing time when returning service from a ball machine compared to a player. Such discrepancy may be explained by a decomposition between perception and action that has a significant impact on the anticipation and action preparation, due to a failure to access the relevant kinematic information from the server (Shim, Carlton, & Kwon, 2006; Pinder, Renshaw, & Davids, 2009). In recent years, research has begun to consider the perception-action coupling in the tennis service and focused on both the developmental stages of players technique as well as determining whether commonly used coaching methods provide the most effective skills development (Giblin, Whiteside, & Reid, 2017; Whiteside, et al., 2015). An emphasis on effective coaching regarding perception-action coupling in a framework of a representative learning environment could expose players to a wide variety of performance contexts that would be beneficial for skill development (Reid, Whiteside, & Elliott, 2011). Of specific interest within tennis is examining how kinematic adaptations in the active limbs occur in self-paced skills such as the service, in situations with a great deal of similarity between the competitive performance context and the practice environment. Therefore, the primary aim of this study was to explore how multi-segment coordination patterns are re-shaped under different environmental constraints during a tennis serve. A secondary aim was to investigate the association between service time variability and coordination patterns.

Methods

Participants

Following institutional ethics approval, 10 (9 males and 1 female) expert tennis players (age: 34.1±5.3; height: 178.5±8.9; body mass: 80.3±14.3) volunteered to take part in this study. The majority of participants were right-handed (70%) and according to the British Lawn Tennis Association, their current ratings ranged between 1.1 and 5.2. All participants were free from injury at the time of testing.

Materials

A 3D wireless motion capture system (STT systems Co, Spain) was used to analyse the tennis service of all participants. The STT-IBS system is a 9-degrees-of-freedom inertial measurement unit (100Hz) that integrates an accelerometer, gyroscope and magnetometer in each of its axes. The system measures the relative orientation, acceleration and position (along the X, Y, Z axes) of the STT-IBS sensors and has previously been used to accurately measure joint angles in different multi-joint movement patterns (Setuain, Gonzalez-Izal, Luque, Andersen, & Izquierdo, 2017).

A seven segment upper body model comprising the right and left hand, right and left forearm, right and left upper-arm, head and torso was utilised. All sensors were securely attached to the segments using elastic straps so that the X, Y and Z axes were oriented in the sagittal, frontal and transvers planes, respectively. The torso sensor was used as the reference sensor, but was not included in the kinematic model.

A digital high definition webcam (25Hz) was used for identification of the start and the end points of the movement, as well as the different stages of the tennis service (Kovac & Ellenbecker, 2011). The camera was placed 10 metres away and at 45˚ to the service area and was time synchronised with the collection of the sensor data.

Procedure

Participants performed a 10 minute general warm up followed by a series of tennis specific drills normally seen in a tennis-specific match warm-up. Participants were asked to perform a series of serves from behind the baseline in three different conditions: control, target and opposition. In the control condition, there was no opponent and participants were asked to serve to an empty court. In the target condition, a tripod (H:2m, W:0.6m) was placed 40cm behind the baseline on the returner’s side of the court in order to replicate the typical position a returning player may stand when receiving serve. Participants were asked to serve with a view to achieving success in the point. In the opposition condition, participants served against a similar standard opponent who was free to stand anywhere on court. The order of conditions was randomised with all participants' completing10 successful serves (landing in the service box) per condition. Participants were given 20 seconds rest between trials and 3 minutes rests between conditions to prevent any fatigue effects.

Data analysis

Upper body kinematic movements were determined using a 17 DoFs model: right and left wrist joints (2 DoFs: flexion-extension; radial flexion-ulnar flexion), right and left elbow (2 DoFs: flexion-extension; pronation-supination), right and left shoulders (3DoFs: flexion-extension; abduction-adduction; rotation) and head (3DoFs: flexion-extension; lateral rotation; rotation).

Raw data were smoothed using a Butterworth 2nd order low pass (10Hz cut-off frequency) filter before joint angles were calculated. Angular displacements in a related plane were extracted for service according to the 8-stage model proposed by Kovac and Ellenbecker (2011). The stages identified were 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). For the purposes of this study, the start of the action was defined as the beginning of the release stage (stage-2) and the end of the action following the racket-leg landing (stage-8). The service time was calculated from stage-2 to stage-8 of the action. These key points defining the start and end of the service action were identified using video footage of individual serves. Due to differences on service duration between trials and participants, all trials were interpolated in Matlab (Matlab, 2015a, The Mathworks) as a percentage of service time (0-100%). Normalised trials for each individual joint angle were averaged for each participant across 10 trials for each condition.

A principal component analysis (PCA) was used to quantify the coordination patterns and synergies in the tennis service. PCA as a reduction technique allows the grouping of individual joint motions into functional units (O'Donoghue, 2008) which is beneficial for quantification of complex motor skills (Witte, Ganter, Baumgart, & Peham, 2010). The PCA method was used to examine how much variance of the service is defined in terms of changes among related joints and time (joints × time series matrix). The orthogonal varimax rotation was used to calculate the total variance and the principal components (PCs) during the entire service. The resultant PCs or eigenvectors are linear combinations of original data as orthogonal axes that determine the majority of the total variability of joint motion in the entire service action. 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, principal component (PC) load vectors were allocated to each time series point. The eigenvectors, PC loading vectors, are defined as a correlation between each PC and joints motions. Two criteria were selected for extracting joint variance as a PC. Firstly, if the saturation level for total variance was greater than 90% (Deluzio, Harriosn, Coffey, Caldwell, 2014), then the extracted PCs are strong predictors of joint variance in the entire service. Secondly, a joint motion (variable) was included in the predictive model if its correlation with the extracted PC was above 0.50 (Jackson, 1993).

The PCA method in this study was used in two ways. Firstly, the individual PCA was calculated separately for each participant and then the mean of PCs among them was calculated as a pooled PCA per condition. A total of 17 × 101 matrix [joints × time series] per participant in each condition was recorded. Each matrix gave a total variance and individual variance per PC. We compared 3 conditions on both the total variance and individual PCs from the available matrices by repeated-measures analysis of variance (ANOVA). Secondly, the mean joint angles of each participant were averaged for each condition and the new PCA was calculated from this mean joint matrix; 101 × 17 [service point percentage × joint motion].

The inter-trial variability in service time was calculated using the standard deviation of 10 service attempts per condition. Pearson correlation (two tailed) coefficients were used to correlate between PCs and service time variability at the 95% confidence interval.

Results

The PCA analysis extracted 4 PCs after varimax rotation in all conditions (see Figure 1 and Figure 6). The results of the ANOVA showed no significant difference in total variance and individual PCs between conditions ($p>0.05$). The extracted PCs are named according to the nature of joint motions (variables) that were grouped into a synergy (see Figures 2-5).

****Table 1 near here****

Table 1 summarises the levels of synergies, functions and the stages of the service action for each condition.

The first extracted PC displayed the largest variance across conditions, it determined the *maximum height reaching* (PC_1= 41.68±5.55%) in the control condition, while *setting up* was defined (PC_1= 40.93±6.47%) in both the target and opposition conditions (PC_1= 40.18±9.92%). In the control condition, this emergent coordination pattern was used for reaching the maximum height during the acceleration and ball contact stages of the action, whereas in both the target and opposition conditions, it was used for setting up the service during the ball toss in the non-racket arm (loading stage).

The second coordination pattern (PC_2) was identified as the *forward kinematic chain* with similar variance seen across conditions (Control= 24.8±4.4%; Target=25.36±4.11%; Opposition: 26.73±4.51%). The function of PC_2 was different among conditions in terms of the service stage and purpose. In the control condition, the f*orward kinematic chain* was utilised for finishing the service after ball contact and prior to and within the deceleration stage. However, in the target condition it was only used prior to ball contact in the acceleration stage of the action. In the opposition condition, this function was changed to hit the ball with maximum force during the contact stage.

The third PC_3 had a versatile role across the different service conditions. It was used to throw the shoulder during the contact stage (*extending shoulder*; PC_3= 15.93±2%) in the control condition, while in the target condition it played a supplementary role in *extending the forward kinematic chain* through contact

(PC_3= 15.93±4.53%). In the opposition condition, it played a role in *counter-movement loading* in an in-phase coordination action during the cocking phase (PC_3= 15.74±6.89%).

The final coordination pattern (PC_4) was mainly applied to decelerate the racket arm in all conditions. More specifically, it was used to decelerate the service action at stage 7 as *contralateral deceleration* (PC_4= 9.24±6.58%) in the control condition, for final adjustment prior to contact and follow-up deceleration (PC_4= 8.05±5.72%) after contact in the target condition, and for *contralateral acceleration-deceleration* (PC_4= 7.91±5.89%) at stages 5-7 of service for both acceleration and deceleration of the racket arm in the opposition condition.

****Figure 1 near here****

****Figure 2 near here****

****Figure 3 near here****

****Figure 4 near here****

****Figure 5 near here****

****Figure 6 near here****

The results of Pearson correlation coefficients showed that PC_2 was the only coordination pattern that determined the service time variability in the control ($r=0.57$, $p<0.05$) and opposition conditions ($r=0.58$, $p<0.05$). Therefore, by increasing the degree of variance in PC_2, the amount of inter-trial variability in service time was increased.

Discussion

The primary aim of this study was to explore how multi-segment coordination patterns are re-shaped under different environmental constraints during a tennis serve. Findings showed that the contribution of different upper body joints in the tennis serve can be grouped into 4 multi-segment coordination patterns that are responsible for control of the non-racket arm in the initial phase of the action and the racket arm both before and after the racket-ball contact. A secondary aim was to investigate the association between service time variability and coordination patterns. Findings showed an increased variance in coordination patterns used to control the kinematic chain of the racket arm (PC_2), and was significantly associated with inter-trial service time, regardless of condition. The current study showed that one way that expert players use the available degrees of freedom in the upper body limbs during the tennis serve is through developing functional coordination patterns among active segments to contribute in different stages of the service. Our results show that four functional patterns emerged in expert players in all conditions, but that the extracted PCs had different roles in the execution of the service. Regardless of the environmental condition, non-racket arm motion to set up and reach the maximum height (PC_1) had the largest variance (40-41% of total variance) in comparison to other synergy units (PCs); however, the remaining variance (>50%) was determined by racket arm motions. The coordination patterns that emerge among independent body segments offer greater flexibility to the motor system to achieve the desired performance outcome (Latash, Scholz, & Schoner, 2007; Gelfand & Latash, 1998), allowing the body to re-organise movement patterns (Davids, Glazier, Araújo, & Bartlett, 2003). As we showed in our findings, the execution of the tennis service required 4 synergic components that define joint variability in different stages of the serve. The results failed to show any significant difference in total variance and individual PCs between conditions. This lack of difference may be due to the level of expertise of the performers, the number of trials completed and the environment. Research suggests expert performers are able to fine tune the action according to the situational demands without significant changes in body mechanics (Davids, et al., 2015; Dickinson et al., 2000; Williams, et al., 2015). For example, Williams et al. (2015) showed that expert gymnasts had less variability in coordination patterns (shoulder-hip couple) during a longswing relative to novices. The present study used expert players who might use a similar fundamental movement pattern with small changes based on the situation. This might explain the lack of difference between conditions. In addition, the physical environment did not completely pressurise the participants in the same way as a real match.

A further explanation for the lack of difference between conditions may relate to the use of only 10 trials, which might not have been enough to change the kinematic variability during the service due to the nature of the action (self-paced skill). Despite similarities in overall variance between conditions, the grouping of joint motions into related PCs was different in some instances between conditions. For example, in the target and opposition conditions, PC_4 had a larger contribution in the pre-contact and contact phases to allow for final adjustments and acceleration of the racket arm; whereas, in the control condition, PC_4 was mainly involved at the deceleration stage of the movement. This, in turn, could give more flexibility to the motor system to adjust the body according to the situational requirements (e.g. acceleration and deceleration). The dependency to condition also occurred for PC_3 when the opposition condition afforded a different perceptual attunement for the performers to re-calibrate the movement pattern (Stone, et al., 2015b). In fact, instead of contribution in racket-ball contact time, it was used for loading the racket arm prior to contact. This discrepancy in temporal patterns among conditions might be explained in terms of the physical effort that was required to beat the opposition player by using a powerful service. This may have been facilitated through the storage of elastic energy in the wrist and shoulder before ball contact (Wilson, Elliott, & Wood, 1991) and the adaptations based on the perception of environments (Carvalho et al., 2014).

We demonstrated that the movement dimensionality during the serve is organised into functional units as synergies. Synergies have context-sensitive roles; depending on the action context, they can function as a brake, a spring and as a motor (Dickinson et al., 2000). As functional units rather than anatomical assembly, they are more flexible to certain situations (Gelfand, Gurfinkel, Tsetlin, & Shik, 1971). This might explain how the highest level of skill in a specific task or sport, is acquired through elaborating the coordination variability. This study showed that one of the characteristics of advanced adaptations in expert performers is how to configure the redundant segments into meaningful behaviours, such as forward kinematic chain, acceleration and deceleration.

Unlike PC_3 and PC_4, PC_1 and PC_2 had a more consistent role in the serve and were mainly involved in setting up the ball toss and forward kinematic chain, respectively. Despite the anatomical similarity in different environmental conditions, they differ in terms of the stage of service (see Table 1).

The association between the level of coordination and the extracted variance suggested that some components of a technique such as tossing the ball by the non-racket arm in PC_1 are consistently performed because the related pattern (re)emerged with fewer inter-trial fluctuations. In contrast, the racket arm required exploiting the flexibility in joint configurations to adjust the service in some stages; mainly for contact and afterwards. More specifically, the variance that was defined by the racket arm always had 3 PCs in all conditions. The non-racket arm is mainly used in the first and second stages of the service (start and release), and due to its simple role during the action, it was subject to less inter-trial variability. On the other hand, the racket arm as a main effector depends on the requirements of the situation in different stages of service. The results of the Pearson correlations also confirmed this fact that the kinematic chain in the racket arm (PC_2) significantly predicted the service time variability in both the control and opposition conditions. The main role of effectors on performance is also demonstrated in other sports. For example, Federolf et al. (2014) showed that "body inclination during alpine skiing is an important feature of the technique and determined over 50% of total variance in elite ski racers." Furthermore, Bockemühl, Troje and Dürr (2010) studied hand movements during catching and showed that inter-joint synergies that were defined by 3 PCs often varied with regard to the target location. Neurobiological degeneracy gives more flexibility and re-invention to a motor system to adapt to the situation without any changes in the performance outcome (Chow et al., 2008). In this study, results suggest that players used the racket arm to exploit joint variability differently to meet the mechanical requirements of the service, such as angular and linear velocity, momentum, elastic energy and coordination (Elliott, Reid, & Crespo, 2003).

The findings of this study have implications for the acquisition and refinement of the tennis service action. Firstly, the recruitment of all available joint motions as a functional unit in different stages of the serve is a major milestone in the acquisition of a proficient skill. Coaches need to facilitate this process in novice players through task-related practice. Secondly, coaches need to be aware that the dynamic interaction between environment and performer, even in a self-paced skill like the serve, could change the functional coordination patterns among the active joints. As a result, they need to utilise functional variability through proper task practice drills and employ tasks so that the amount of practice with and without a real opponent is taken into account. Lastly, due to non-significant differences between conditions in terms of total variance, it seems that expert players quickly adapted to different environmental situations with subtle changes in the service technique. Coaches should setup practice contexts so that integration of joint DoFs into functional units is facilitated for consistent performance.

We acknowledge some limitations within the present study. Firstly, the biomechanical model used to quantify the service technique excluded the trunk and legs, as a result, the coordination of whole body actions was not considered. Future studies could use a full-body biomechanical model during the tennis service. Secondly, it is difficult to draw any conclusions regarding the adaptation pace in expert players due to the lack of a control group, for example comparison to a group of novice players. In fact, using a control group could be informative to demonstrate how the kinematic adaptations to different environmental constraints are shaped. Thirdly, performance factors such as ball velocity and accuracy were not measured or controlled in this study. It is likely that the velocity-accuracy trade-off could be key in helping to understand changes in the coordination patterns during the serve. Future studies should control these variables to examine the association between body dimensionality and environmental constraints through taking into account the other variables in more complex scenarios.

Conclusion

In conclusion, this was the first study that examined the effect of environmental constraints on multi-segment coordination patterns in the tennis service. The findings demonstrated that expert performers reduce the joint complexity by creating functional coordination patterns in different phases of the service and adapt the service action according to the situational demands.

Strengths and weaknesses

1- The first study that emphasises the mechanical adjustments due to environmental demands in tennis service.

2- Using expert performers to execute the service action was strength of this study.

3- There was a need to extend the number of trials to stabilise the movement pattern.

4- Lack of control group to compare the results was another weakness of this study.

Declaration of interest

The authors report no declarations of interest.

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Table 1- Features of synergies in different stages of tennis service

Control Condition	PC_1	PC_2	PC_3	PC_4
Level	4-segment	3-segment	3-segment	2-segment
Function	Maximum height reaching	Forward kinematic chain	Throwing shoulder	Contralateral deceleration
Service stage	Acceleration-Contact	Deceleration	Contact	Deceleration
Target Condition				
Level	4-segment	3-segment	1-segment	2-segment
Function	Setting up	Forward kinematic chain	Extended Forward kinematic	Final adjustment and deceleration
Service stage	Loading	Acceleration	Contact	Acceleration-Contact-Deceleration
Opposition Condition				
Level	4-segment	3-segment	2-segment	3-segment
Function	Setting up	Forward kinematic chain	Counter-movement loading	Contralateral acceleration-deceleration
Service stage	Loading	Contact	Cocking	Acceleration-Contact-Deceleration

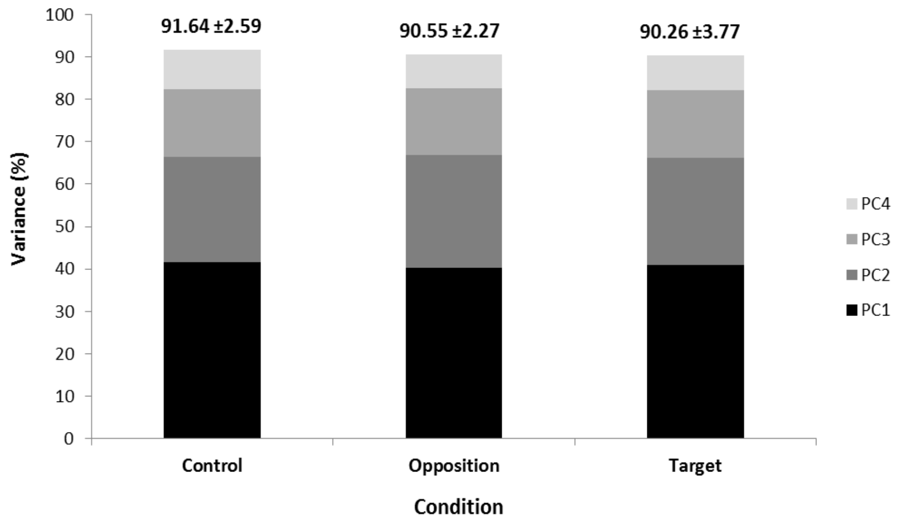


Figure 1- Mean total variance and individual PC variances in different task conditions

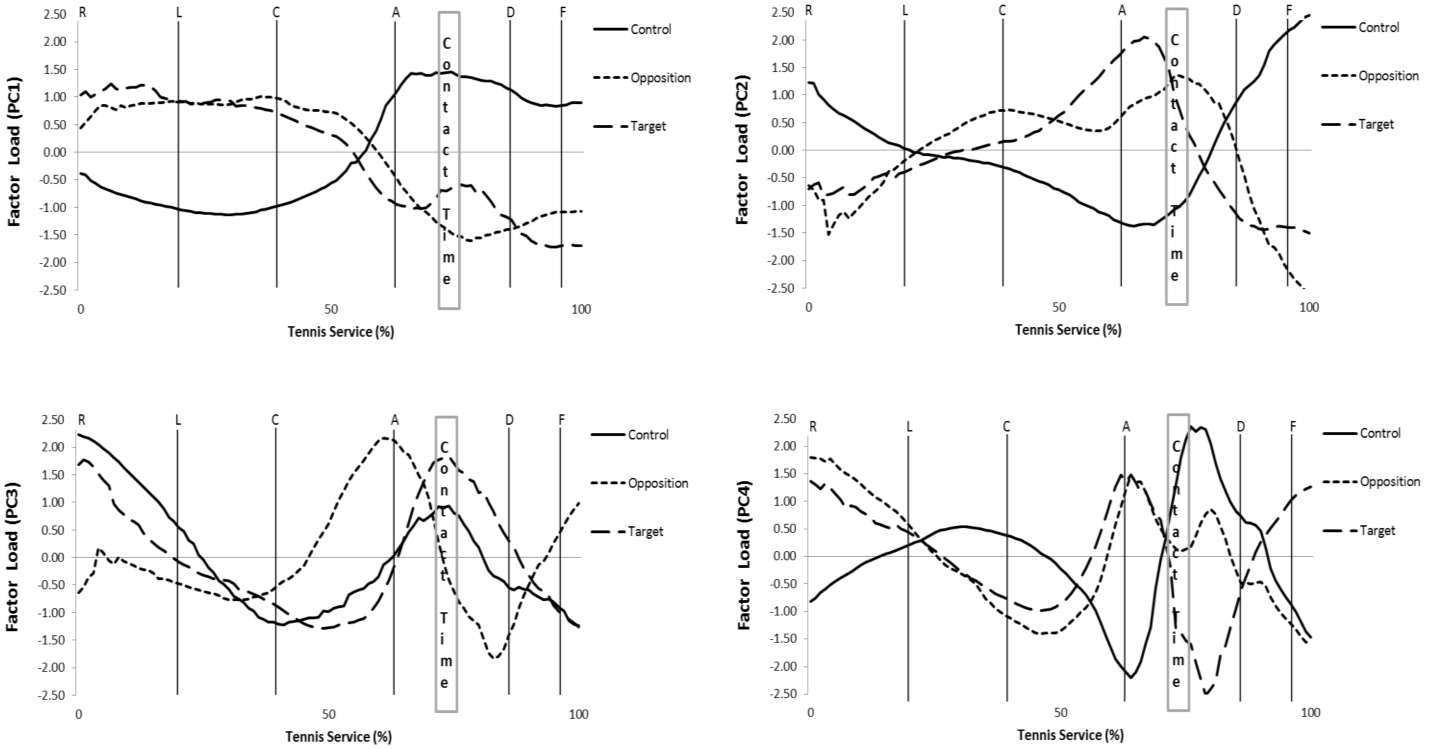
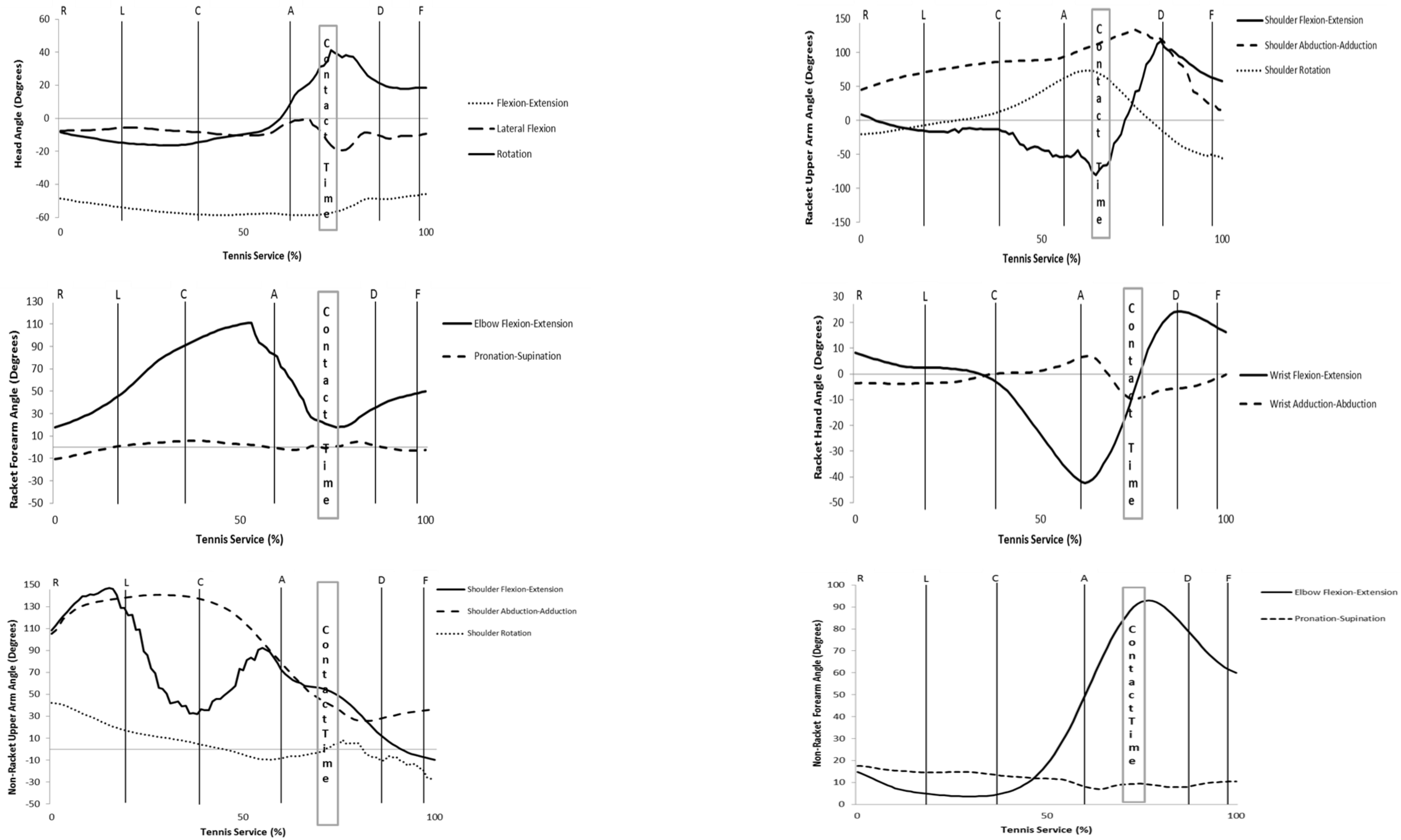


Figure 2-Factor loading of different PCs in entire service action in different conditions. The stages of service are separated by the vertical lines; Release (R); Loading (L); Cocking (C); Acceleration (A); Contact; Deceleration (D) and Finish (F).



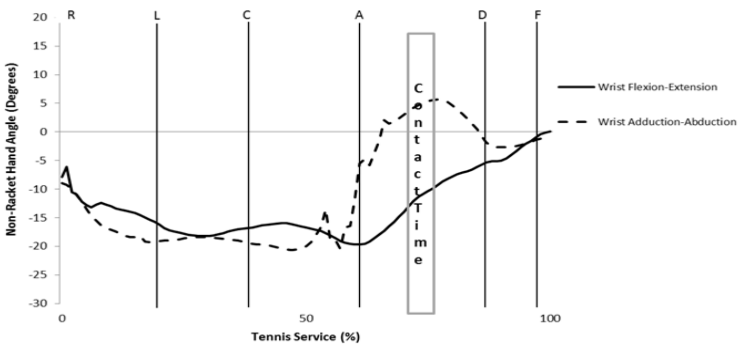
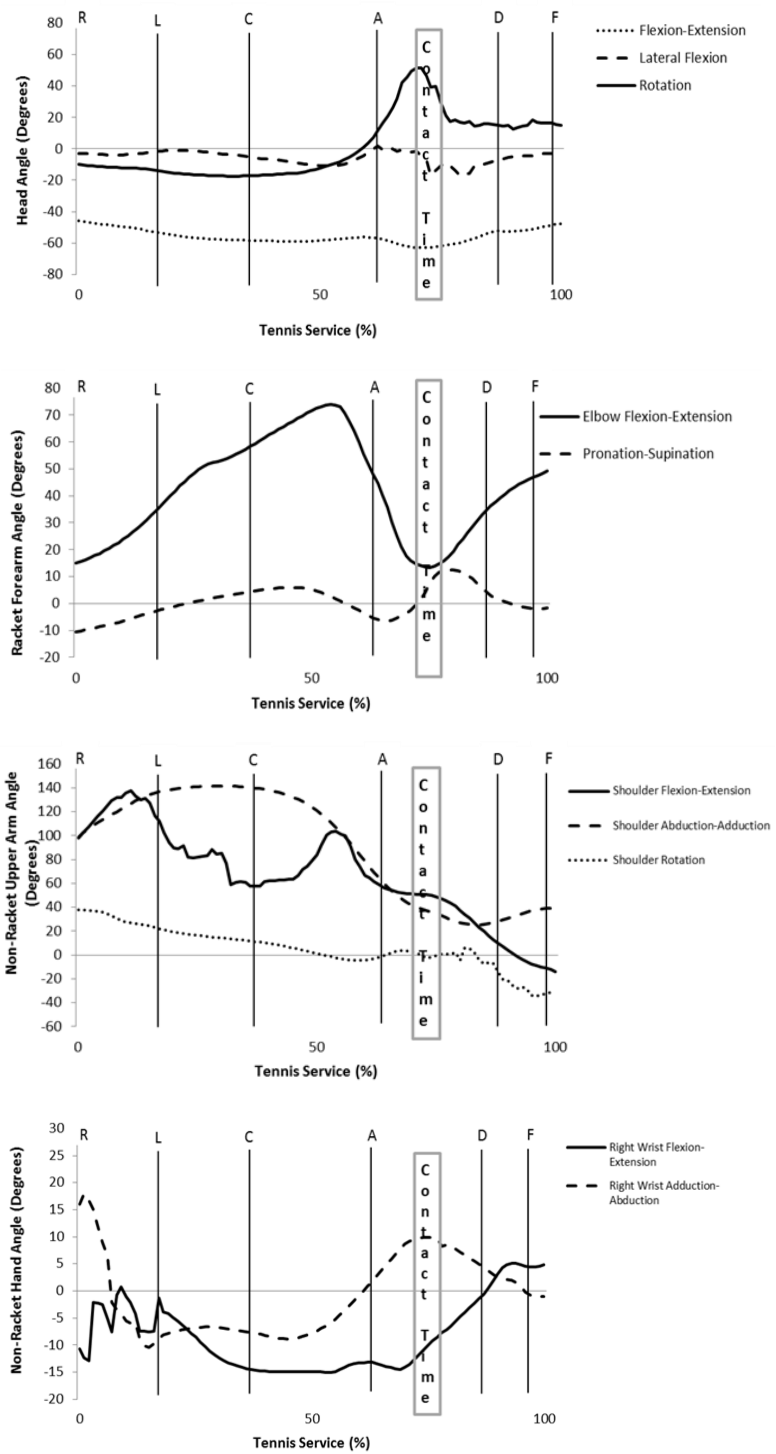


Figure 3- Mean angular displacement of different body segments during service in control condition



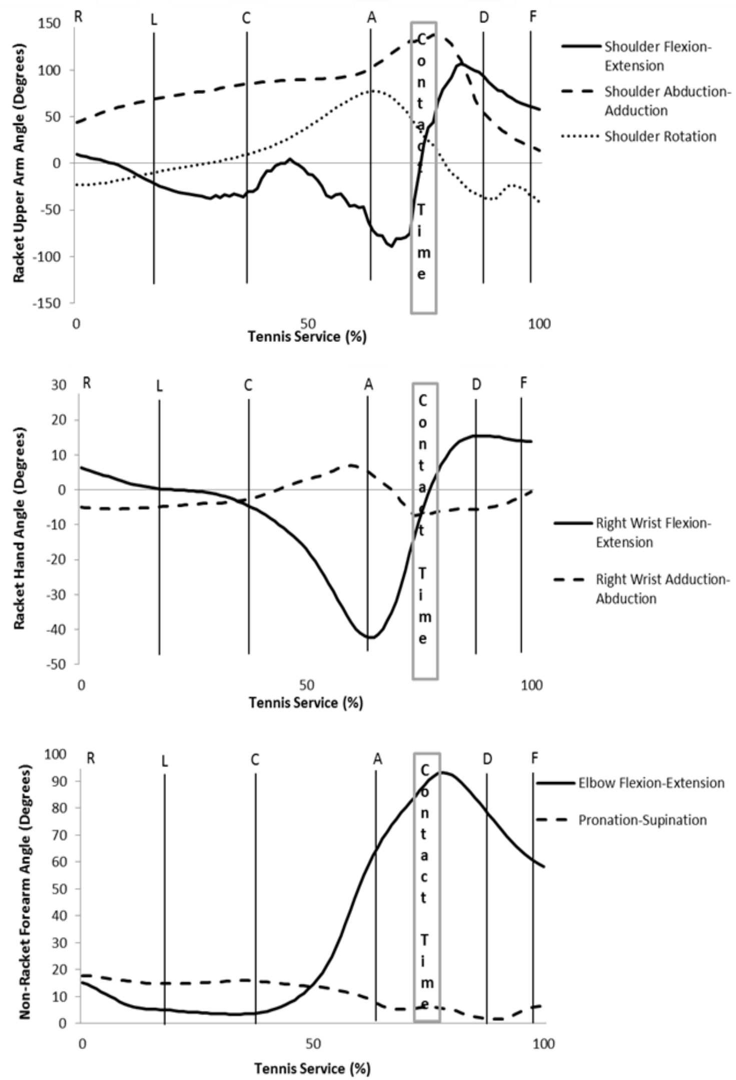
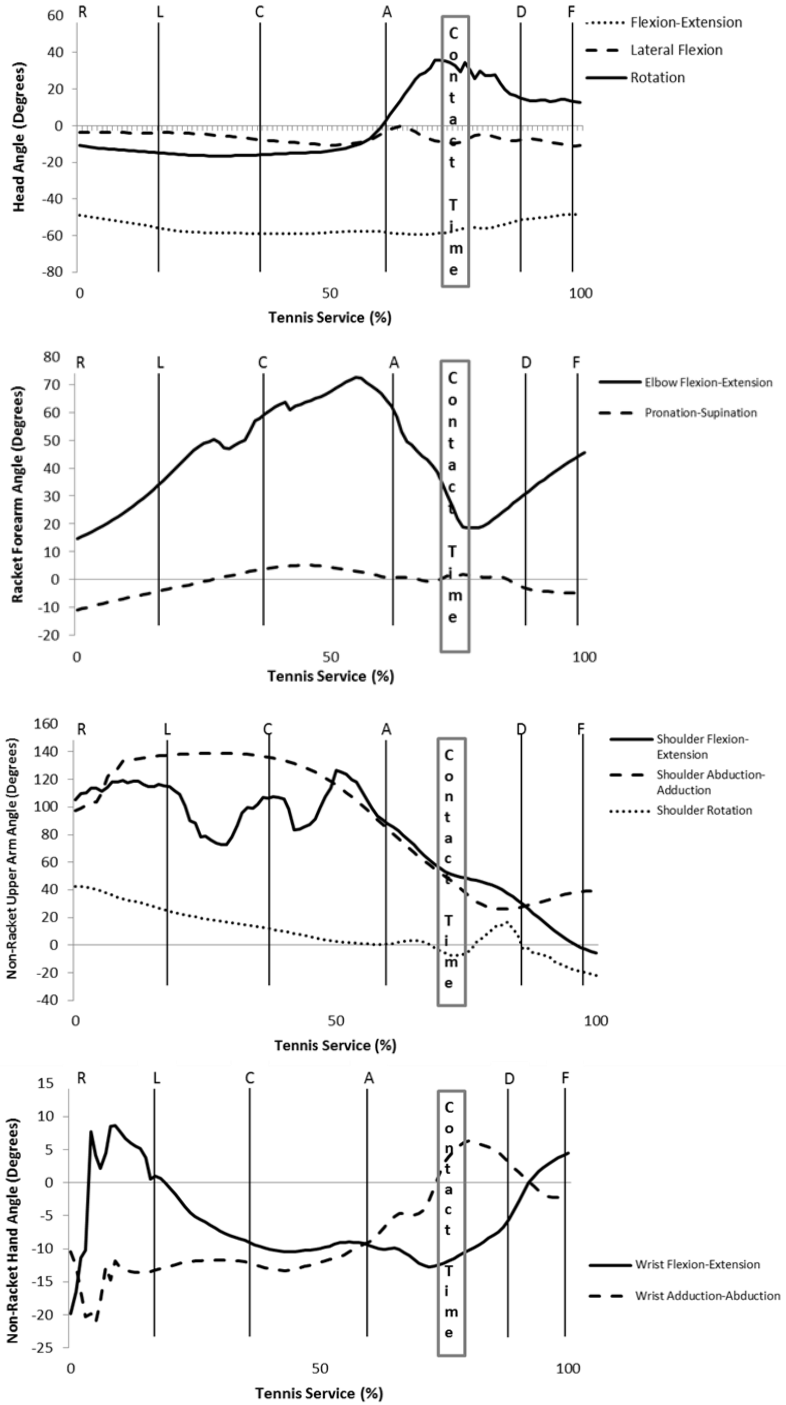


Figure 4- Mean angular displacement of different body parts during service in target condition



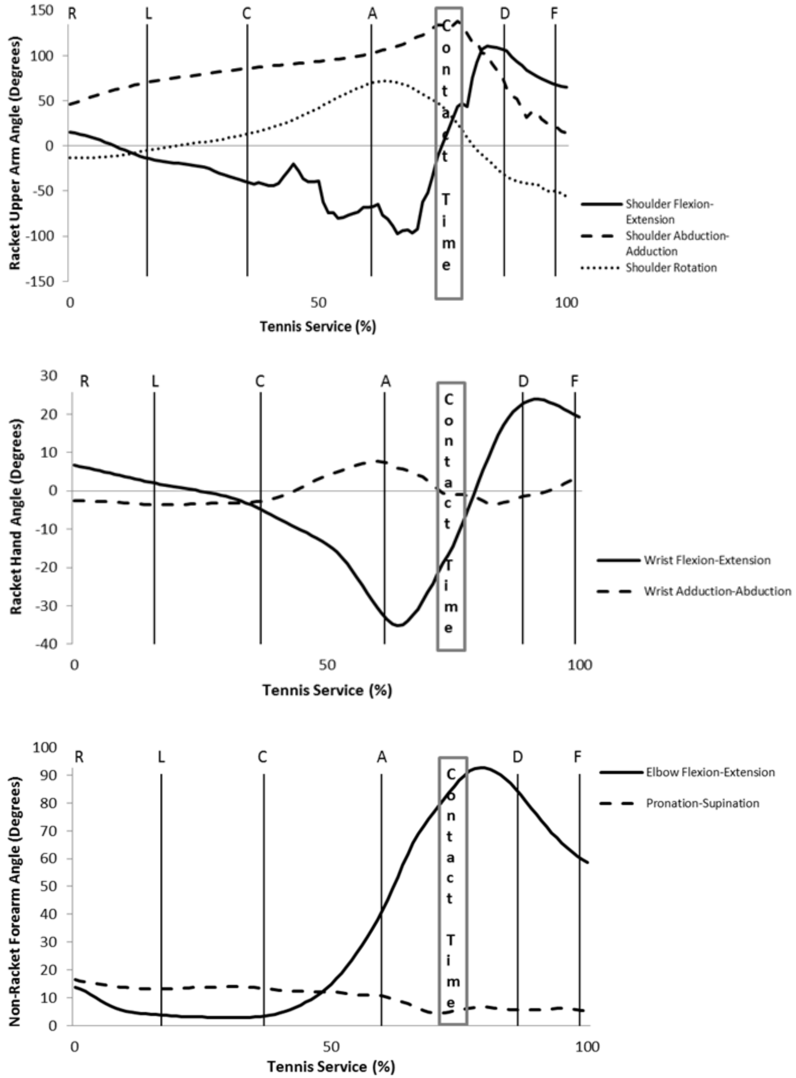
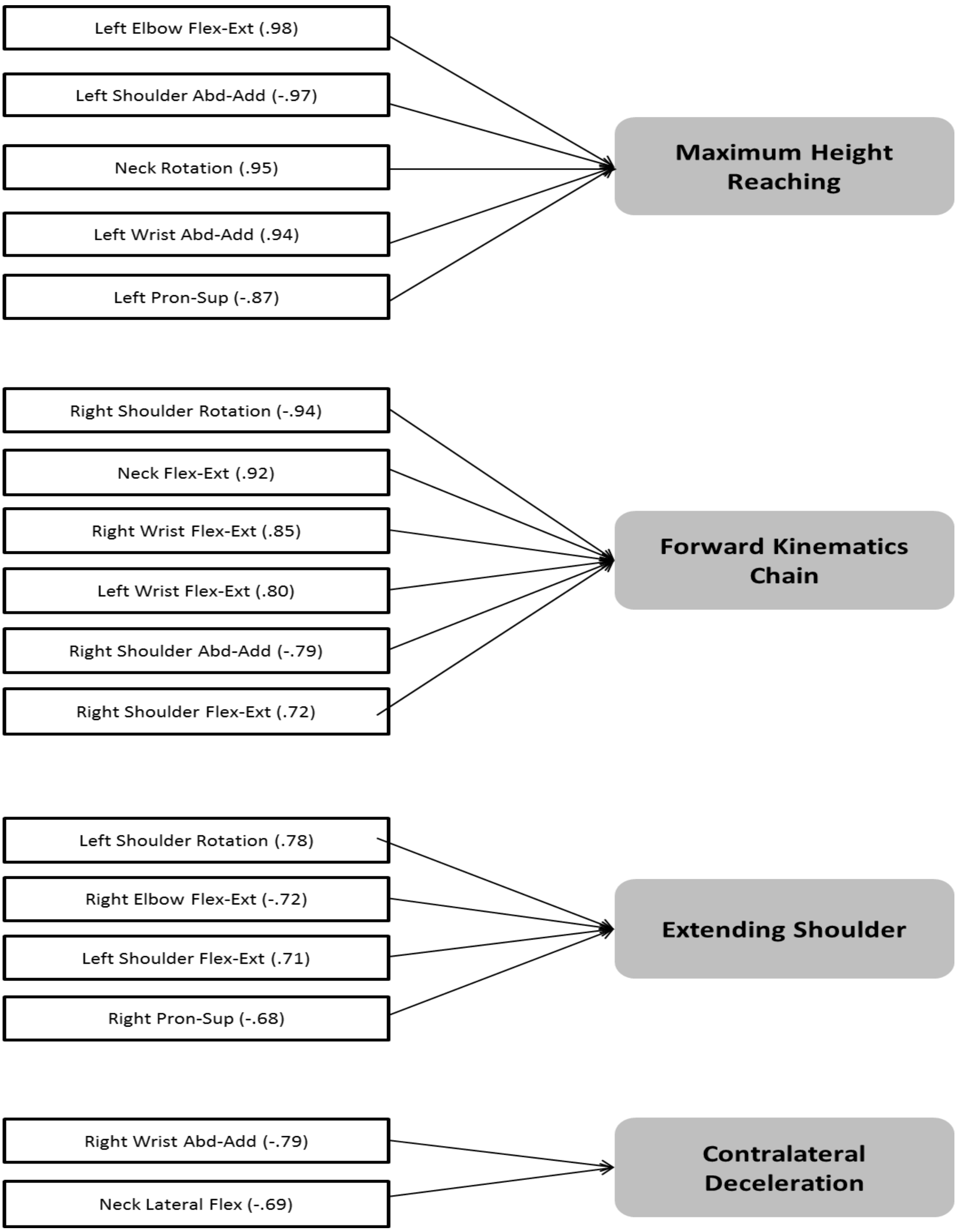
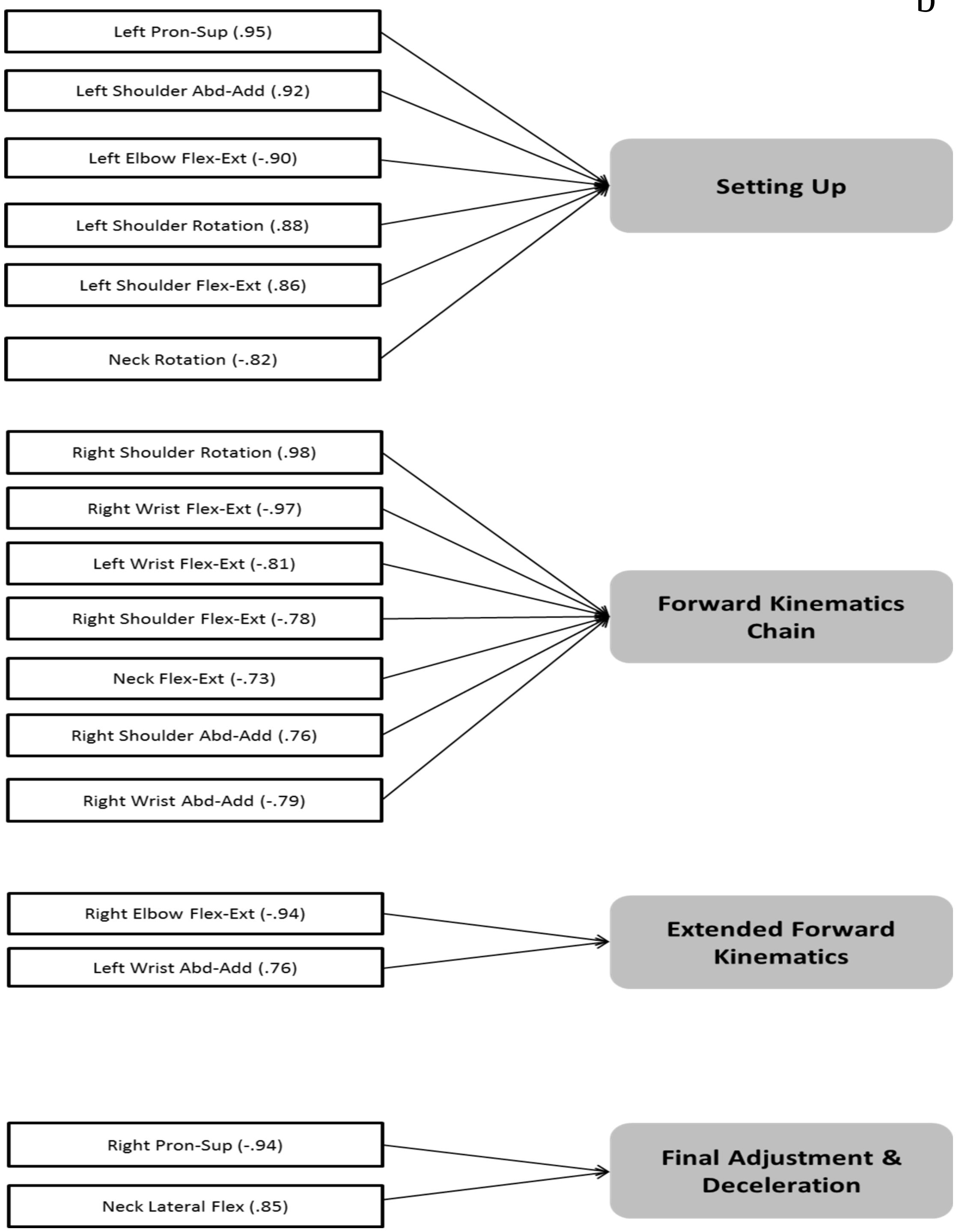


Figure 5- Mean angular displacement of different body parts during service in opposition condition

a


Left Elbow Flex-Ext (.98)
Left Shoulder Abd-Add (-.97)
Neck Rotation (.95)
Left Wrist Abd-Add (.94)
Left Pron-Sup (-.87)
Maximum Height Reaching
Right Shoulder Rotation (-.94)
Neck Flex-Ext (.92)
Right Wrist Flex-Ext (.85)
Left Wrist Flex-Ext (.80)
Right Shoulder Abd-Add (-.79)
Right Shoulder Flex-Ext (.72)
Forward Kinematics Chain
Left Shoulder Rotation (.78)
Right Elbow Flex-Ext (-.72)
Left Shoulder Flex-Ext (.71)
Right Pron-Sup (-.68)
Extending Shoulder
Right Wrist Abd-Add (-.79)
Neck Lateral Flex (-.69)
Contralateral Deceleration

b


Left Pron-Sup (.95)
Left Shoulder Abd-Add (.92)
Left Elbow Flex-Ext (-.90)
Left Shoulder Rotation (.88)
Left Shoulder Flex-Ext (.86)
Neck Rotation (-.82)
Setting Up
Right Shoulder Rotation (.98)
Right Wrist Flex-Ext (-.97)
Left Wrist Flex-Ext (-.81)
Right Shoulder Flex-Ext (-.78)
Neck Flex-Ext (-.73)
Right Shoulder Abd-Add (.76)
Right Wrist Abd-Add (-.79)
Forward Kinematics Chain
Right Elbow Flex-Ext (-.94)
Left Wrist Abd-Add (.76)
Extended Forward Kinematics
Right Pron-Sup (-.94)
Neck Lateral Flex (.85)
Final Adjustment & Deceleration

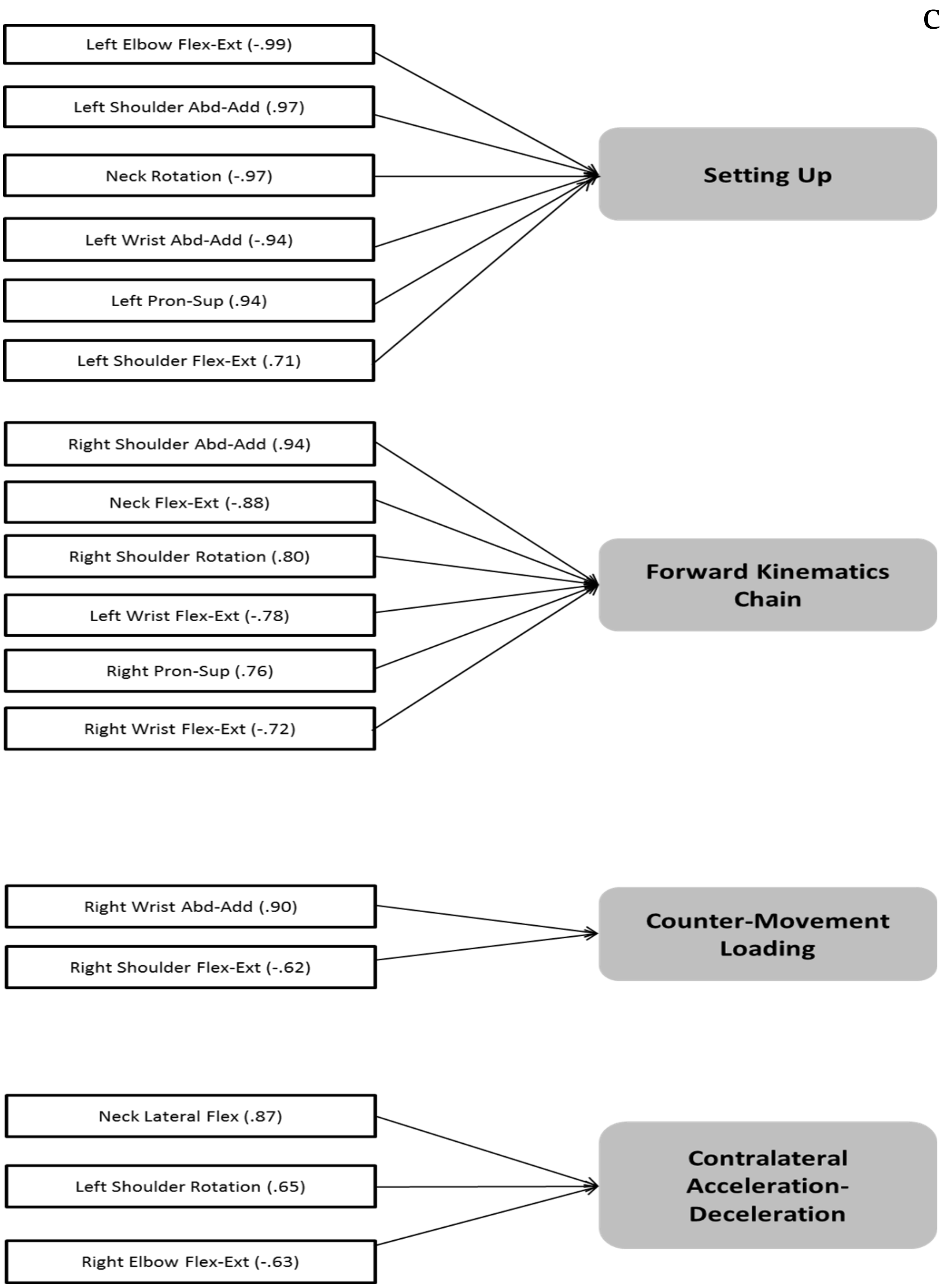


Figure 6-Relationship between segments and components after varimax rotation in control condition (a), target condition (b) and opposition condition (c)