Field-based upper-body motor variability as determinant of stroke performance in the main tennis strokes

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Performance in tennis relies heavily on the skilful repetition of several types of tennis strokes, yet the role of motor variability has still received little scientific attention – especially at a within subject level. The present study aims to evaluate the role of motor variability depending on the strokes/body segment and the level of expertise. Thirty-five players performed a field test (including first and second serves, forehand and backhand strokes) with four synchronized gyroscopes placed on trunk, head, upper arm and forearm. Variability was measured based on the coefficient of variation (CV) of the angular velocity peaks per stroke in each body segment. MANOVA revealed greater motor variability in the forehand and backhand than in the serve ($p < 0.001$), with head and forearm segments showing the highest variability (CV > 15 % in some cases). This also translated in differences in variability between levels of expertise, with variability being greater in the players of lower level ($p < 0.02$ in all strokes, with Cohen $d > 1$ in some cases). Summarized, groundstrokes could imply more compensatory kinematics movements – about all in head and forearm – to keep the result of the action stable. Motor variability has to be considered to evaluate performance, as a reduced motor variability was found in players with higher level of expertise. The compensatory action of the body segments (especially in groundstrokes and in the arm and head, where the coefficients of variation were high) should be studied in depth since it can help design motor tasks, making them more specific.

Keywords: MEMS; racket sports; motor learning; motor flexibility, adaptability, performance.

Introduction

Variability in the performance of sports skills is important to the performance itself, for the development of skills, and in experimental research.[1] The study of motor variability as applied to sports actions has been carried out by specialists in the area of motor control and, until recently, has been largely overlooked by sports biomechanics.[2] Motor variability has traditionally been associated with motor noise generated in the central nervous system, creating a limiting factor to technical performance.[3] In fact, the *theory of dynamic systems* differentiates between motor coordination variability and outcome variability. For this reason, in a goal-directed task, outcome variability in terms of the result of the action, is intended to be stable for optimal performance.[4,5] Motor coordination variability relates to the underlying movements, which must be modified according to the conditions of the environment (extrinsic factors such as wind or irregular ground) or alterations related to athlete self-reports (intrinsic factors such as perceived confidence or fatigue).[5,6] In a similar line Bartlett et al.[7] indicate that motor coordination variability could have a compensatory function since a variation of one execution parameter is compensated by changes in other movement parameters so that outcome variability can be minimised.[8] Therefore, from a dynamical systems perspective, a higher level of technical performance requires a higher level of motor coordination variability and a lower level of outcome variability. In the case of tennis, motor variability has been studied mainly with respect to the serve,[8–11] the forehand,[12,13] the variability in target accuracy, i.e. the way in which the ball bounces are distributed on the court,[14,15] or how the variability of the racket's trajectory affects target accuracy.[16,17]

Differences in variability between strokes and between segments may reflect the mechanical idiosyncrasies of each type of stroke and the mechanical actions of the different segments. In other words, analyzing motor variability in throwing tasks could aid to evaluate the action of different body segments and to study the coordination strategies used. Based on the *theory of dynamic systems*, this knowledge could reveal much about the strokes and segments where compensatory movements have special importance. Wagner et al.,[18] analysed handball throws and found greater variability in the distal joint segments (associated with a compensatory function that may help to ensure a suitable throwing), similar to what Button et al.[19] had found for basketball shooting (they suggest that compensatory motions of the elbow and wrist joint serve to adapt to changes in release parameters of the ball). In tennis strokes, where high speed of the distal joints is reached and where subtle changes in racket trajectory could differentiate between successful and unsuccessful shots[16] it would be interesting to study the variability of the different body segments and compare the differences depending on the stroke. When designing specific task, the focus should be on the adaptability of the strokes and limbs with the highest variability values. This could be done, for example, by including tasks where random elements are included (for example balls with an irregular bounce) that require kinematics compensatory movements to keep the result of the action constant. Despite all these studies, there is hardly any work comparing motor variability between the three main tennis strokes, i.e., the forehand, the backhand and the serve.

The analysis of variability between player's levels of expertise can reveal important information about how skilled players satisfy situational constraints[19], helping us improve our understanding of motor coordination of complex movements.[18] It could help in deciding whether to take variability as a variable related to performance, and not only the segmental contribution as normally done.[20,21] Wagner et al.[18] found a decrease in movement variability in highly skilled handball players and Lees & Rahnama[1] also suggest that highly skilled football players may be able to demonstrate less variability in the reproduction of a skill associated with a constrained task (e.g., hitting a ball to a target). On the contrary in basketball free-throws, Button et al.[19] found that improvement in skill level was associated with increased movement variability, and explain this founding based on the aforementioned *theory of dynamic systems*. Others have found that variability shows a *U-shaped* curve in relation to the skill level of the athlete[22] differentiating between random variability (present in novices) and active functional variability (that of expert players). In the particular case of tennis, movement variability is believed to negatively impact serve performance by reducing both speed and accuracy of the ball[9]. However, Whiteside et al.[23] showed that increased motor variability did not reduce serve accuracy. Nevertheless, these studies analyse variability at the within-subject level and do not consider the level of play as an independent variable so the relationship between motor variability and the level of expertise is not clear and should be studied further.

Following the above discussion, the present study aims to compare the intra-subject motor coordination variability of the main tennis strokes – i.e., groundstrokes and serves – by treating both the level of expertise and the body segment as independent variables. The hypothesis of the study is that mechanical differences between the different strokes and segmental actions will induce different values of variability (having higher values in the distal segments that will have a functional or compensatory function) and that the highest-level players will be those with the lowest motor coordination variability scores. Strengthening knowledge of the strokes/body segments that present the highest values of motor variability could improve the process of designing motor tasks. The results of this could also provide information on whether the kinematic variability allows differentiating between game levels in the particular case of tennis.

Method

Participants

A total of thirty-four tennis players of different ages and levels participated in this study. According to the International Tennis Number[24], 12 players could be classified into level 2-4 players (advanced players; age = 27.8 ± 9; height = 180.3 ± 6.5; weight = 77.3 ± 7.7; body fat percentage = 12.9 ± 2.5; body mass index = 23.7 ± 1; skeletal muscle mass = 38.3 ± 3.8), 12 players into level 5-6 (intermediate players; age = 34.4 ± 9.4; height = 176.4 ± 5.9; weight = 77.9 ± 13.2; body fat percentage = 18.5 ± 8.5; body mass index = 25.1 ± 4.4; skeletal muscle mass = 35.7 ± 2.9) and 10 players into level 8 (recreational players; age = 27 ± 11.2; height = 177.9 ± 6.3; weight = 73.9 ± 10.9; body fat percentage = 17.6 ± 3.9; body mass index = 23.3 ± 2.5; skeletal muscle mass = 33.5 ± 4.2). Body composition was tested through bioimpedance (Inbody 230, Inbody, Seoul, Korea).

Inclusion criteria for the participants in this study were: (i) reporting normal vision and no history of any neuropsychological impairments that could affect the results of the experiment, (ii) not presenting any injuries during the previous two months, (iii) giving consent, and (iv) not having engaged in vigorous physical activity in the previous 48 hours.

The participants were informed about the main goals of the investigation and signed informed consent forms. Participants were informed that they could revoke the participation agreement at any time. The tennis players were treated according to the American Psychological Association (APA) guidelines, which ensured the anonymity of participants' responses. In addition, the study was conducted following the ethical principles of the *Helsinki declaration* for human research and was approved by the local research ethics committee.

Procedures

Measurements were performed at the Sport and Health Research Institute (University of Granada). For each player, data was collected only once. To make sure that they met the inclusion criteria they completed a brief questionnaire on general aspects about history of injuries, rest and training. After that they performed the physical tests. A maximum of two players was scheduled per day.

Specific stroke performance test

In the present study motor coordination variability was assessed through multiple *Nexgen IMU sensors* (*Nexgen Ergonomic I2M SXT*, Montreal, Canada; size: 48.5 x 36.5 x 13.5 mm^3; weight: 22 g), which have been shown to be valid for analysing angular kinematics in tennis strokes by comparing them against a photogrammetric motion capture system.[25] The study participants were fitted with 4 *Nexgen inertial sensors* (synchronized with each other, at a sampling frequency of 128 Hz) placed on the trunk, head, upper arm and forearm.[25] In the present study the z-axis of the head sensor was manually aligned with the vertical.

The specific stroke performance test was based on previous research.[26] Before beginning the test, an 8-minute warm-up was performed which consisted of joint mobility exercises and a 5-minute rally (2 service lines and 3 baselines) with an expert trainer (always the same). The stroke test was performed on a hard court with acrylic surface of type A[27] and each player used their own racket. A check was carried out in order to make sure that they were in a good state and approved by the ITF.[27] Also racket string tension was measured with a string tension meter (Tourna Stringmeter), in order to verify that all rackets had an adequate and similar tension. A correlation of 0.98 (Pearson r square) was reported between this device and a tensiometer ProsPro model MQT.[26]

All participants in the study performed a series of serves (including 10 first serves and 10 second serves) and two series of groundstrokes (including each series 10 forehands and 10 backhands, hitting both alternately). Therefore, per player there were 10 first serves, 10 second serves, 20 forehand and 20 backhand groundstrokes. This number of strokes was based on previous research analysing motor coordination variability of acyclic gestures.[1,28] The angular velocity peaks of each segment were evaluated for motor coordination variability, and the ball speed for outcome variability. Other studies analysing motor variability of sporting actions had also relied on the analysis of segment or joint angular velocities.[5]

The ball speed was measured using a Stalker Pro II radar, with an accuracy of ± 1 km/h according to the manufacturer. The stroke performance test was similar to previous studies using a ball throwing machine to standardize the trajectory of the approaching ball.[29] Subjects were asked to hit as fast as possible while still maintaining the best accuracy values. Accuracy was analysed using the methodology of the study by Delgado et al..[26] In the case of the forehand and backhand series, two 2 m x 2 m targets were placed (one in each corner of the court) and the shots were classified as *good shots* (%) when they entered the baseline rectangle but did not hit the target, *very good shots* (%) when they hit the target or *out shots* (%) if the ball hit the net or did not enter the two aforementioned targets. In the case of service, the target was placed in the corner closest to the centre line of the court and the shots were classified in the same way (the *good shots* were those that entered the service box). In the study by Delgado et al.[26] an illustration of the test and the scoring targets is shown (the difference is that in this case the ball was served by an expert coach). Three minutes of rest was allowed between series to prevent any influence of fatigue.

Analysis of the angular velocity signal

As the gyroscopes appear to have an internal filter and consequently very low white noise levels,[25] the untreated sensor output signals were used. This aligns with other studies conducting variability analyses, expecting to obtain a more accurate representation of the variability within the system.[30,31] The OriginLab software was used to determine the angular velocity peaks corresponding to each stroke. Angular velocity peaks were selected in a spike pattern and close together, to ensure that the peak occurred during the stroke (See Figure 1 for more information). A description of the signals on each of the axes of the gyroscopes is described in the following lines. Firstly, we selected the angular velocity peaks largely due to the turning action of each segment along its longitudinal axis (trunk rotation, arm internal/external rotation or forearm pronation/supination movements) which above all corresponds to the angular velocity peak of the sensors of the trunk, upper arm and forearm on the x-axis (from now trunk-x, arm-x and forearm-x). They were negative on the serve and on the forehand, and positive on the backhand. The angular velocity peaks due to the rotation of the head along its longitudinal axis or angular velocity peaks of the head sensor on the z-axis (head-z) were also chosen. They were positive on the forehand and on the serve, and negative on the backhand. The angular velocity peaks related to adduction/abduction movements of the arm/forearm (arm-y and forearm-y) were positive on the serve and on the forehand, and negative on the backhand. Finally, the angular velocity peaks due to flexion/extension of the arm and forearm in a fundamental position or arm-z and forearm-z were selected. In the case of the arm, they were positive on the serve and on the forehand and negative on the backhand. In the forearm, they were positive on the forehand and negative on the serve and backhand.

--------Figure 1 near here--------

Statistical analysis

The statistical analysis was carried out with the OriginLab software, with R and with the Real Statistic Using Excel tool.[32]

As a measure of motor coordination variability, the coefficient of variation (CV) in percentage was used, by dividing the standard deviation by the mean and multiplying the result by 100. The use of the CV to assess motor coordination variability is common.[1,9,28,33] The average of the angular velocity peaks was also used as a descriptive parameter for the data. Prior to the calculation of means and CVs, outliers were removed with a conservative filter based on the median and the Median Absolute Deviation (MAD).[34] Those peaks whose magnitude was between the median and the MAD multiplied by ± 5 were selected. The conservative value of 5 times the MAD was used to eliminate a small number of strokes.

To study the contribution of the selected variables on the ball speed, the partial correlation coefficients between each angular velocity variable and the ball speed were calculated and a multiple linear regression analysis was performed using the peaks of angular velocity as predictor variables and the ball speed as output variable. The quality of the correlations was assessed using the *Evans scale,*[35] which establishes the following levels: i) 0.00-0.19, "very weak"; ii) 0.20-0.39, "weak"; iii) 0.40-0.59, "moderate"; iv) 0.60-0.79, "strong"; v) 0.80-1.0, "very strong". Variance inflation factors were also calculated to study possible multicollinearity problems. An inflation variance factor above 10 was selected to indicate multicollinearity problems.

To compare the motor coordination variability between the different strokes, a non-parametric repeated measurement MANOVA in R was performed using the Wild Bootstrap option and Tukey multivariate post-hoc comparisons,[36] including the type of stroke as independent variable and the coefficients of variation of the angular velocity peaks as dependent variable. This process is clarified in Figure 2. In addition, repeated measures ANOVAs were made to study the differences between strokes in each of the angular velocity peaks analysed. In this case the post-hoc analysis was carried out using the Tukey HSD test. The effect size (Cohen d) was provided by the Real Statistic using Excel software. To interpret the magnitude of the effect size we adopted the following criteria: d= 0.20, small; d= 0.50, medium; and d= 0.80, large.

--------Figure 2 near here--------

For comparing variability between levels of expertise a single measure of variability per stroke was selected (as the mean of the CV for each segment). This allows to compare the total 1st serve, 2nd serve, forehand and backhand variability depending on the level of expertise (a one factor ANOVA per stroke was performed for that purpose). Tukey HSD was used to carry out post-hoc analyses (computing the effect size using the Cohen d).

The significant p value was established at $p < 0.05$ in the case of the: i) MANOVA (and corresponding post-hoc analysis), ii) regressions and iii) ANOVA (and post-hoc analysis) performed to compare variability according to the levels of expertise. In the case of the repeated measures ANOVA and in the corresponding post-hoc analysis, the p-value was set at 0.001 (taking into account the number of comparisons made, to reduce the probability of committing type I error).

Results

Few outliers per stroke and per variable were eliminated. In the case of serves, 100% of the angular velocity peaks were selected. In the case of forehand, more than 19 angular velocity peaks per player and per segment were selected (19.6 ± 0.41 peaks). Only in the case of the head-x 17 peaks were selected in one of the players. In the backhand, something similar occurred and in all cases more than 18 angular velocity peaks were selected per player (19.7 ± 0.6). Only one player recorded 17 angular velocity peaks in the trunk-x.

The percentage of *out shots, good shots* and *very good* shots was 55 ± 20 %, 8 ± 9 % and 38 ± 19 % for the first serve and 42 ± 23 %, 6 ± 11 % and 51 ± 23 % for the second serve. For forehand and backhand the percentages were 42 ± 15 %, 39 ± 14 % and 19 ± 12 % and 40 ± 16 %, 45 ± 15 %, 15 ± 10 %. Average ball speeds were 134 km/h, 111 km/h; 101 km/h and 91 km/h for the 1st serve, 2nd serve, forehand and backhand, respectively. The speed CVs were 6 %, 8 %, 11 % and 10 %, respectively. The averages and CV averages for the peak segment angular velocities are shown in Table 1.

--------Table 1 near here--------

As for the partial correlations between the measurements of angular velocity and stroke speeds (table 1), strong correlations were found on the 1st serve, for the arm-x, forearm-x and forearm-z (figure 3a); on the 2nd serve for the forearm-z (figure 3b); on the forehand for the trunk-x (figure 3c) and on the backhand for the arm-x (figure 3d) and forearm-y. Moderate correlations were also frequent. Multiple linear regression models explained the ball speed variance by 62% ($p < 0.001$; $F = 7.72$), 47% ($p < 0.001$; $F = 4.64$), 62% ($p < 0.001$; $F = 7.70$) and 44% ($p = 0.002$; $F = 4.21$) for 1st serve, 2nd serve, forehand and backhand (Figure 4). The average of the variance inflation factors for the multiple linear regression model for the 1st serve was 2.8 (the maximum was 5.7), 3.0 for the 2nd serve (maximum 6.4), 1.6 for the forehand (maximum 2.1) and 2.4 for the backhand (maximum 5) indicating that multicollinearity was not a concern.

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--------Figure 4 near here--------

The non-parametric repeated measurement MANOVA showed significant differences in motor coordination variability between the different strokes (Wald-Type statistic = 274,653; degrees of freedom = 24; $p < 0.001$). Multivariate post-hoc comparisons showed lower values of variability in the 1st serve than in the forehand ($p < 0.001$; estimate = 50.51; lower limit = 21.13; upper limit = 79.88) and lower values for the 2nd serve with respect to the forehand ($p < 0.001$; estimate = 45.56; lower limit = 15.77; upper limit = 75.35). There were also significant differences in the comparison between the 1st serve and the backhand and between the 2nd serve and the backhand, with the variability in the backhand being greater in both cases ($p = 0.007$; estimate = 32.18; lower limit = 5.7; upper limit = 58.66 and $p = 0.044$; estimate = 27.24; lower limit = 0.3; upper limit = 54.18, respectively).

The ANOVAS of repeated measurements showed differences between strokes in motor variability ($p < 0.001$ in all cases) for the: i) trunk-x (1st serve CVs < forehand and backhand CVs; 2nd serve CVs < backhand CVs); ii) forearm-x (1st serve, 2nd serve and backhand CVs < forehand CVs); iii) forearm-z (1st serve CVs < forehand and backhand

CVs; 2nd serve CVs < backhand CVs; backhand CVs < forehand CVs) and iv) head-z (1st serve, 2nd serve and backhand CVs < forehand CVs; 2nd serve CVs < backhand CVs). There were no differences in the motor variability between strokes for the arm-x, arm-y, arm-z and forearm-y.

Finally, there were significant differences ($p < 0.05$ in all cases) in the variability scores between the three levels of expertise for each of the strokes analysed (Figure 5). In the case of the first serve and second serve there were differences between the advanced players and the recreational players and between the intermediate players and the recreational players, being lower in the more skilled players in both cases (Figure 5). In the case of the forehand, advanced players also obtained significantly lower values of variability than the intermediate players and the recreational players (Figure 5). In the backhand there were only differences between the advanced players and the recreational players, with variability being significantly lower in the first group (Figure 5).

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Discussion

For as far as we are aware, our study was the first to assess motor coordination variability across the most common tennis strokes in players of recreational to advanced level. Partial correlations and multiple linear regressions indicated that the selected variables were important for the variance of the ball speed. The MANOVA and ANOVAS of repeated measurements showed a greater variability in the forehand and backhand strokes than in the serves, with greater variability scores in the distal segment (i.e., the forearm) and in the head. There were also differences in motor coordination variability between the advanced, intermediate and recreational players, in all strokes analysed, with variability being lower in the more skilled groups. The difference in motor variability between the main strokes and body segments should be taken into account in the design of the tennis drills as will be further discussed in this section. Also motor variability could serve to differentiate between levels of expertise (lower motor variability indicating a higher level of expertise).

The CVs reported in this study for the different strokes ranged from approximately 5% to 25%. These data are very similar to those of other studies that analysed ballistic gestures with high precision requirements.[1,11,33,37] In the case of the tennis serve for example the coefficients of variation of the humerothoracic joint kinematics reported by Sevrez et al.[11] ranged between 2% and 20% (reaching a CV of 37.2 % for the flexo/extension movement in the cocking phase). In table tennis the CV in the contact and follow-through phase of the shoulder and elbow kinematics for the topspin forehand were a little higher than in the present research (> 30% in the contact phase and >20% in the follow-through phase) but they studied the joint angle and not the angular speed.

The kinematic comparison and motor variability of the different strokes has not often been studied (most studies have analyzed the kinematics of the strokes in isolation) and it is very difficult to find studies that allow us to make a comparison between the different strokes. In the present study CVs were greater in the groundstrokes than in the serves. This could be due to the fact that in the forehand and backhand stroke the ball was thrown by a ball throwing machine and there are more sources of variability, such as the trajectory the ball follows in the air, the bounce of the ball (determined in part by the physical characteristics of each ball) or the movement of the player towards the ball. In the case of the serve, the player is in a more static situation, the ball is thrown by the subject himself, there is no bounce of the ball on the ground and the path is more predictable, thus eliminating possible sources of variability. In support of this hypothesis Ilmane & LaRue[38] suggest that the complexity of an oriented-goal task (they analysed the handball throwing) depend on the differences in the temporal constraint of each task. The coordination of upper- and lower-body effectors, and in consequence the motor variability, is affected by the time constraints, being more complex to perform an anticipation-coincidence condition, such as a groundstroke than a self-initiated throw, such as a tennis serve.[38] In an anticipation-coincidence condition the player has to adjust the posture and the displacements of the body segments in relation to the changing position of the ball, so the subjects modify their behaviour during the throw in each trial. In the self-initiated throw the player determines the start of the movement reducing the complexity of the human-environment system.[38]

The highest values for the CVs were found in the forehand on the forearm-x, forearm-z and head-z (they were 22.7 %, 21.5 % and 25.4 %). In the case of the backhand, the head-z rotation also obtained a high value for the CV (18.7 %). Taking into account that strokes with more topspin imply a greater pronation of the forearm than a flat forehand,[39] the high variability values over the forearm-x and forearm-z are probably related with the differences in the topspin between strokes at a within subject level. Maybe players have modified the topspin effect between strokes in the same series, in order to change the ball trajectory and correct the long or short errors, which could affect variability values. In other words, it is possible for players to alternate between strokes with more or less spin effect, to try to maintain high accuracy thus increasing variability. Another source of variability on the forearm-x could be the unwanted rotations over the longitudinal axis of the racket produced by off-centre impacts. In this line Kentel et al.[40] suggested that the location of the ball impact on the racket strings affects the kinematics of the racket and arm, and an off-centre stroke on the longitudinal axis of the racket could create a moment of force that would cause the head of the racket to turn on this axis and thus rotate the forearm on its longitudinal axis. Wagner et al.[18] or Button et al.[19] also found an increase in movement variability in the distal joint movements during the acceleration phase of throwing actions and suggest that this is due to compensatory movements in this segment (they call it functional variability or compensatory coordination).

As far as the head-z is concerned, the great variability found in forehand and backhand is probably due to the turns of the neck on its longitudinal axis produced during these strokes. Although it has been little studied in the case of tennis, the movements of this segment are a subject of interest to expert coaches, as the head fixation is related with the stabilization of the rest of the body during the execution of the stroke or with the need to extract operational information from the ball.[41] In other sports such as baseball or basketball where accuracy is also an important factor, they have been studied in greater depth.[42,43] The angular velocities of the head during impact could affect the control of movement and the accuracy of the stroke, as can be deduced from the conclusions of the Lafont et al.[41] research, who revealed that elite players show a characteristic fixation of the head in the direction of the contact zone on impact and during the follow-through of the stroke.

Lower motor variability in a closed task (such as those in this study) is indicative of a higher level of technical execution.[1,9,19] Along this line, Wagner et al.[18] found that there was a decrease in movement variability in highly skilled and skilled handball players. In the golf swing[5] and baseball pitch[44], variability of selected kinematic parameters also decreased from unskilled to skilled athletes. In the case of the present work motor variability was lower in the more skilled players in the four strokes analysed, which could be due to a more consistent and regulated performance.[18] On the contrary in basketball free-throws, improvement in skill level was associated with increased movement variability.[19] Consequently, we believe that more studies should be carried out in this regard in tennis, including players from a wide variety of playing levels (i.e., novice players and international players). Considering that motor variability of a close nature task such as the ones in this study is dependent on the level of play it could be considered – additionally to the segmental contribution or ball speed/accuracy as usually done[20,21] – as a performance outcome on the test that evaluates the tennis player's kinematics. In this regard, motor variability has been included as a measure of performance in the evaluation of other ballistic nature skills.[45]

The results of this work suggest that there are differences in motor strategies depending on the type of stroke/segment. This could allow us to improve the design of training tasks, for example, by improving the adaptability of stroke/segments, which are thought to exhibit greater compensatory motor variability. The function of these segments is to correct the action to keep the outcome stable, i.e., to hit with the requested speed and in the requested direction. One exercise that could improve the compensatory motor variability in groundstrokes (that showed the highest values of motor variability), is playing with heterogeneous balls with different bounce characteristics, which may force the player to correct the position of the arm/head in a short period of time. Also playing in different surfaces could avoid an adoption of excessively consistent and unadaptable stroke patterns.

The present study analyses motor variability under relatively stable environmental conditions. This was done in order to reduce the complexity of the motor task and to control undesirable sources of variability. Considering that there are few studies of variability between different strokes in the case of racket sports, it is essential that the first investigations are carried out under simple conditions. Future studies should analyze motor variability in the case of tennis in less constrained situations, including more complex decision-making tasks than in the present work. Considering that the phase of the movement and the characteristics and speed affect motor variability – in throwing tasks, distal segments of the kinematic chain in the final stages have shown higher variability according to Wagner et al.[18] – future research should also analyze motor variability performing a phasic analysis (e.g., backswing, forward swing, and follow-through). The main strength of this work is that it aimed to study the variability in different tennis strokes in an on-court situation, something that has hardly been done to date.

Conclusion

The differences in variability between strokes and body segments should be taken into account when designing personalised training tasks. For example, training tasks that focus on adaptability seem to be especially important in the groundstrokes. Although it has to be studied in depth, the distal segments seem to have higher values of motor variability, probably due to compensatory actions. Finally, given that there were differences in motor variability based on level, we recommend the use of variability measures in performance-oriented tests – which traditionally only have taken into account segmental contribution outcomes and ball speed and accuracy.

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Figures and tables captions

Figure 1. Angular velocity of the signals selected for forehand, backhand and serve. Angular velocity peaks are indicated by a circle. The signals have been filtered (4th order Butterworth filter with 6 Hz cut-off frequency) only to improve visualization.

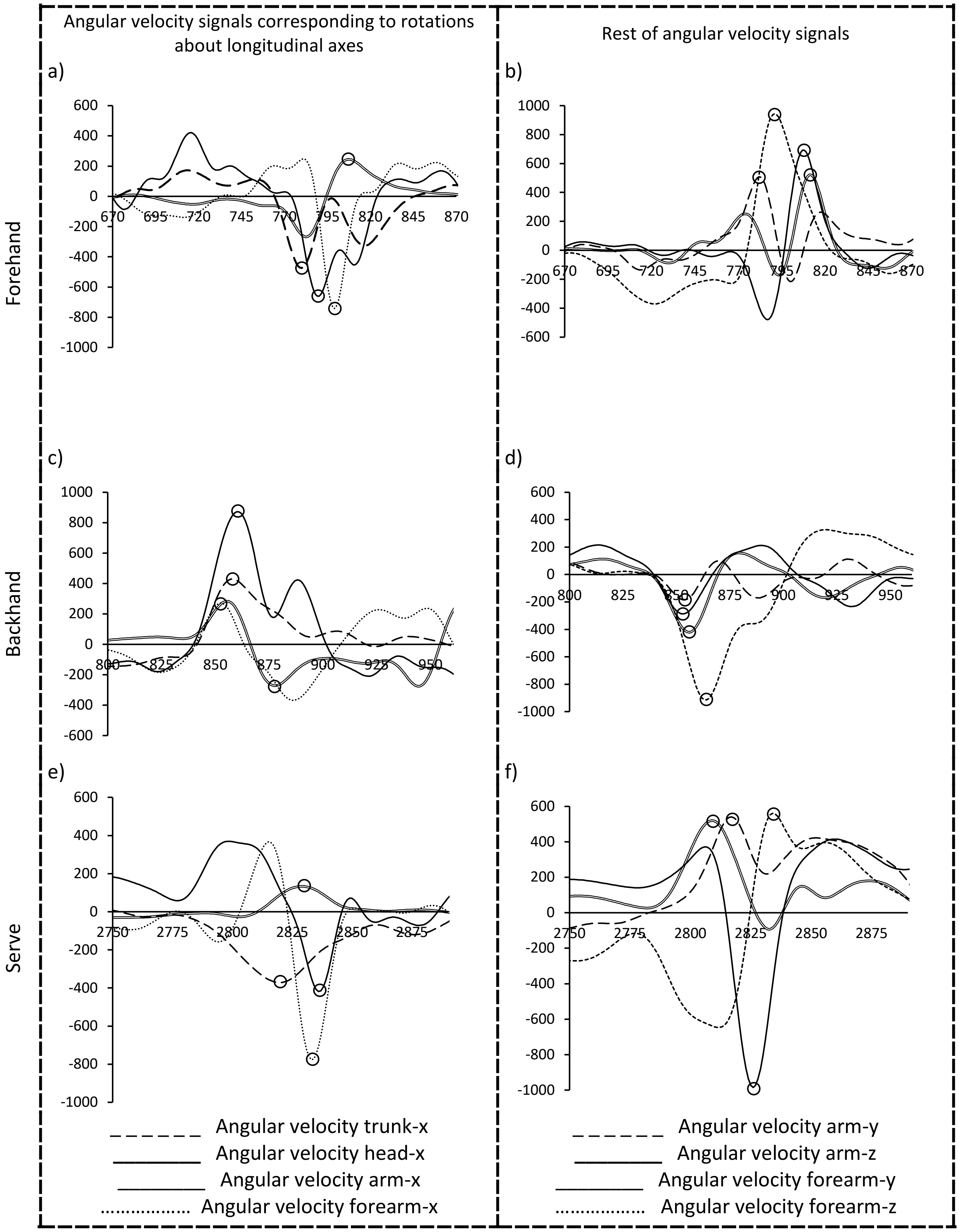
Figure 2. Schematic overview of the statistical procedure to perform the repeated measures MANOVA

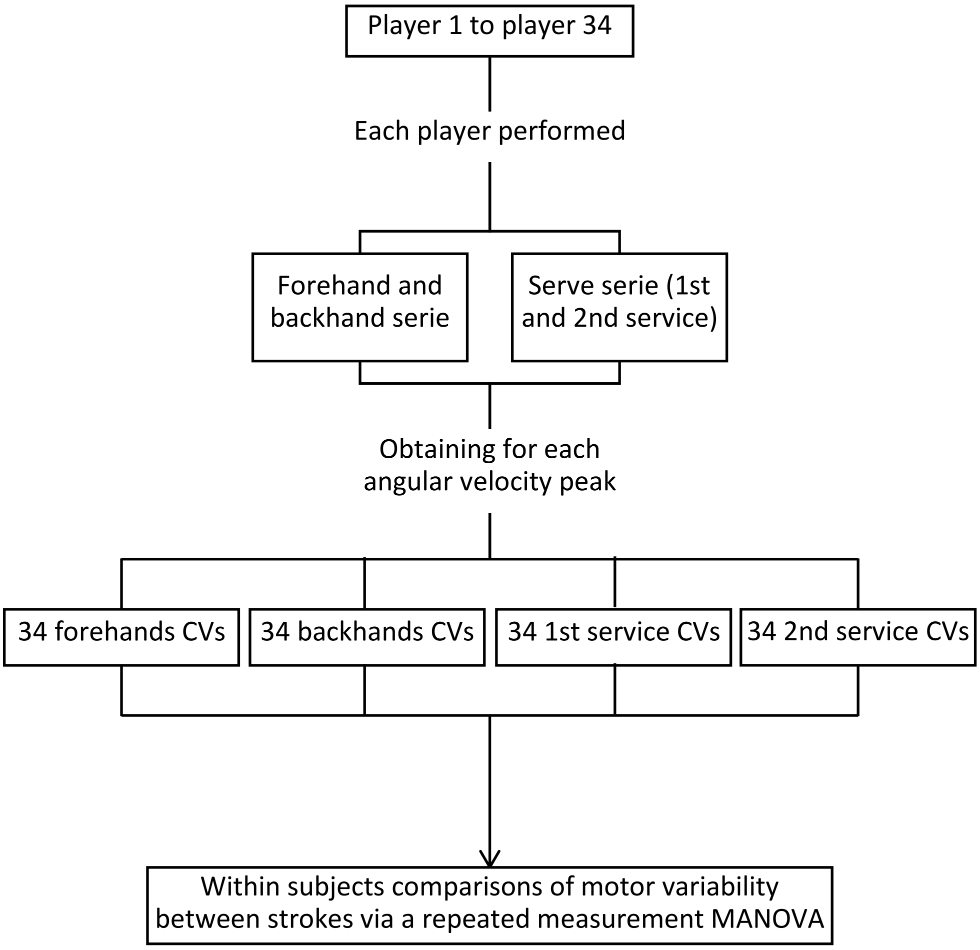
Figure 3. Regression lines of best fit between some angular velocity peaks (means of all subjects analysed) and the ball speed.

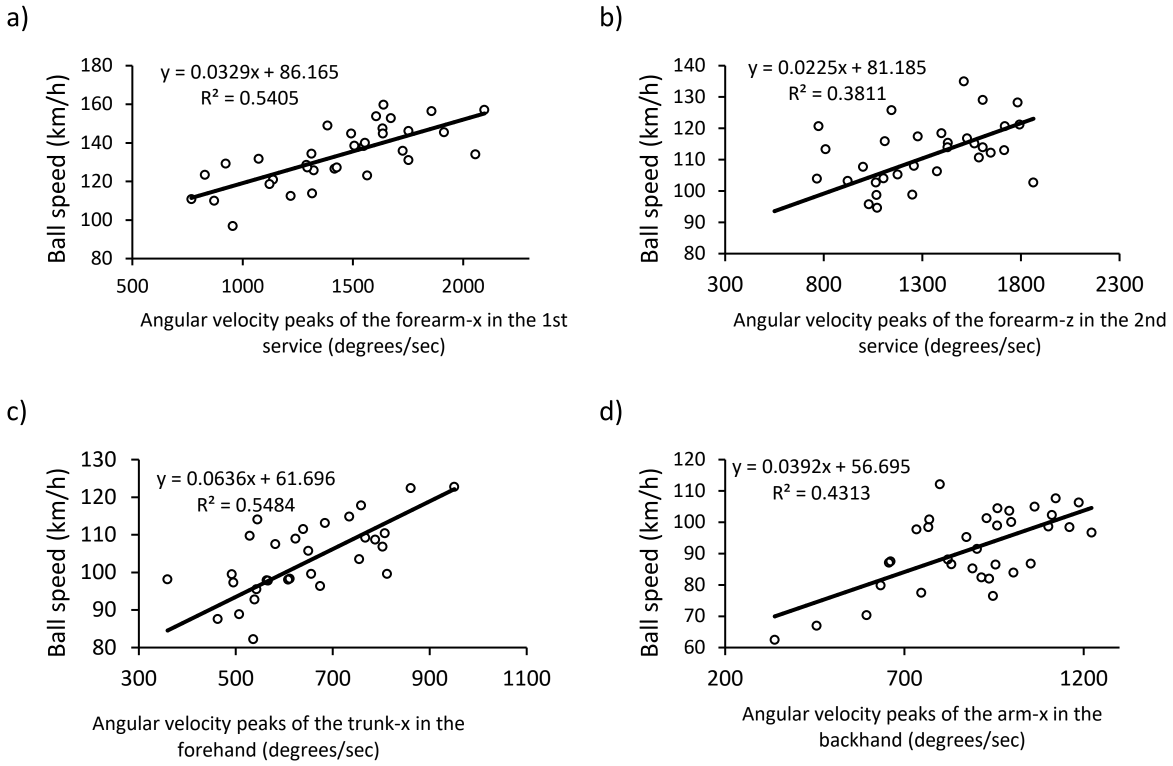
Figure 4. 95% confidence ellipses containing the predicted values of the ball speed regression *vs.* the measured values of the ball speed (km/h). The multiple linear equation with the intercepts and the slope values are included (a, b, c, d, e, f, g and h being the values of angular velocity in degrees/s of the trunk-x, arm-x, arm-y, arm-z, forearm-x, forearm-y, forearm-z and head-z, respectively)

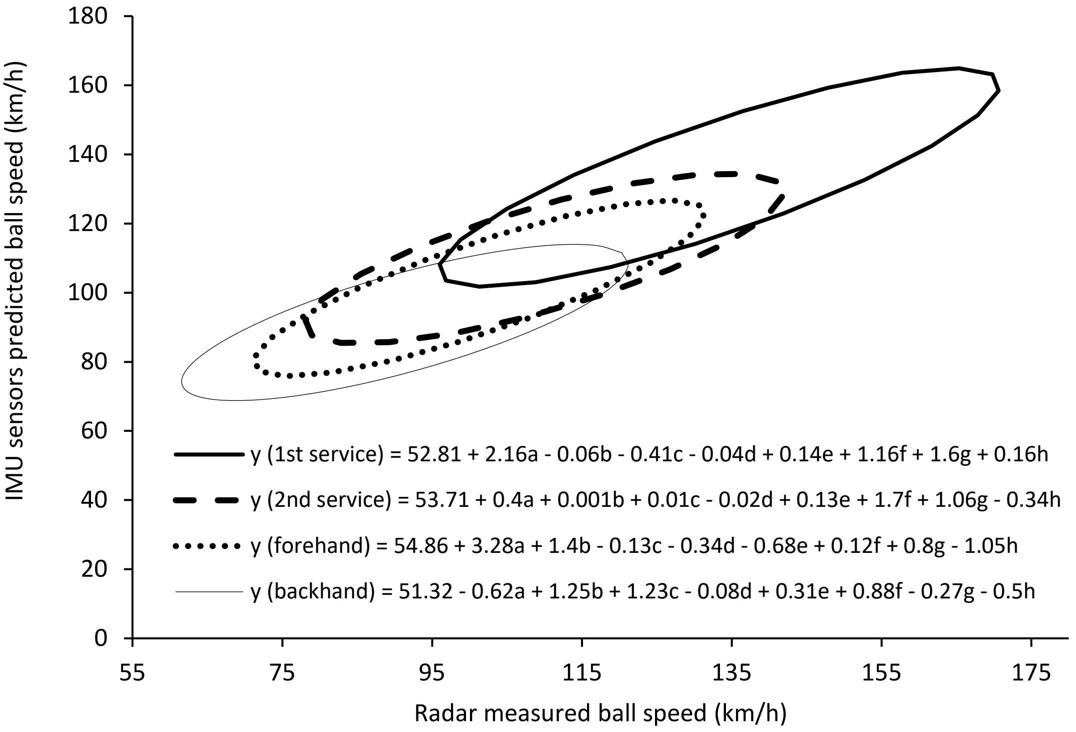
Figure 5. Variability differences between level of expertise in each stroke analysed. Significant differences and effect sizes (Cohen's d values) are indicated in the title of each graph. Adv: Advanced players; Int: Intermediate players; Rec: Recreational players.

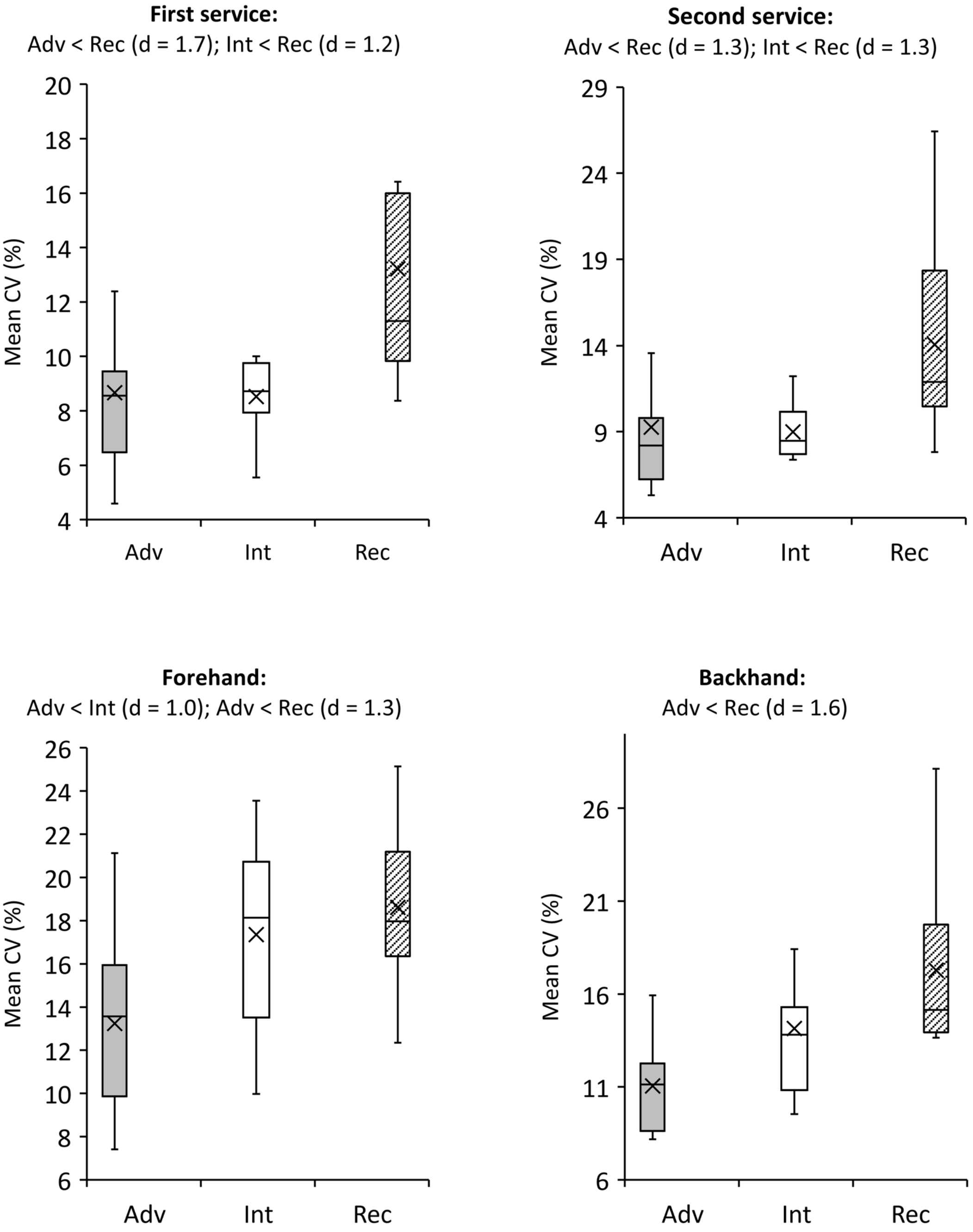
Table 1. Averages (CV averages [%]) of angular velocity peaks (degrees/second) and partial Pearson's correlation coefficients with the ball speed.


Angular velocity signals corresponding to rotations about longitudinal axes
Rest of angular velocity signals
a)
b)
c)
d)
e)
f)
Forehand
Backhand
Serve
600
400
200
0
-200
-400
-600
-800
-1000
670
695
720
745
770
795
820
845
870
1000
800
850
875
900
925
950
825
2750
2775
2800
2825
2850
2875
Angular velocity trunk-x
Angular velocity head-x
Angular velocity arm-x
Angular velocity forearm-x
Angular velocity arm-y
Angular velocity arm-z
Angular velocity forearm-y
Angular velocity forearm-z


Player 1 to player 34
Each player performed
Forehand and backhand serie
Serve serie (1st and 2nd service)
Obtaining for each angular velocity peak
34 forehands CVs
34 backhands CVs
34 1st service CVs
34 2nd service CVs
Within subjects comparisons of motor variability between strokes via a repeated measurement MANOVA


a)
y = 0.0329x + 86.165
R^2 = 0.5405
Ball speed (km/h)
180
160
140
120
100
80
500
1000
1500
2000
Angular velocity peaks of the forearm-x in the 1st service (degrees/sec)
b)
y = 0.0225x + 81.185
R^2 = 0.3811
Ball speed (km/h)
140
130
120
110
100
90
80
300
800
1300
1800
2300
Angular velocity peaks of the forearm-z in the 2nd service (degrees/sec)
c)
y = 0.0636x + 61.696
R^2 = 0.5484
Ball speed (km/h)
130
120
110
100
90
80
300
500
700
900
1100
Angular velocity peaks of the trunk-x in the forehand (degrees/sec)
d)
y = 0.0392x + 56.695
R^2 = 0.4313
Ball speed (km/h)
120
110
100
90
80
70
60
200
700
1200
Angular velocity peaks of the arm-x in the backhand (degrees/sec)


IMU sensors predicted ball speed (km/h)
180
160
140
120
100
80
60
40
20
0
55
75
95
115
135
155
175
Radar measured ball speed (km/h)
y (1st service) = 52.81 + 2.16a - 0.06b - 0.41c - 0.04d + 0.14e + 1.16f + 1.6g + 0.16h
y (2nd service) = 53.71 + 0.4a + 0.001b + 0.01c - 0.02d + 0.13e + 1.7f + 1.06g - 0.34h
y (forehand) = 54.86 + 3.28a + 1.4b - 0.13c - 0.34d - 0.68e + 0.12f + 0.8g - 1.05h
y (backhand) = 51.32 - 0.62a + 1.25b + 1.23c - 0.08d + 0.31e + 0.88f - 0.27g - 0.5h



First service:
Adv < Rec (d = 1.7); Int < Rec (d = 1.2)

Second service:
Adv < Rec (d = 1.3); Int < Rec (d = 1.3)

Forehand:
Adv < Int (d = 1.0); Adv < Rec (d = 1.3)

Backhand:
Adv < Rec (d = 1.6)