Correlations between Angular Velocities in Selected Joints and Velocity of Table Tennis Racket during Topspin Forehand and Backhand

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Abstract

The aim of this study was to determine the correlations between angular velocities in individual joints and racket velocity for different topspin forehand and backhand strokes in table tennis. Ten elite female table tennis players participated, presenting different kinds of topspin forehands and backhands – after a no-spin ball (FH1, BH1), after a backspin ball (FH2, BH2) and "heavy" topspin (FH3, BH3). Range of motion was measured with the BTS Smart-E (BTS Bioengineering, Milan, Italy) motion analysis system with a specially developed marker placement protocol for the upper body parts and an acoustic sensor attached to the racket to identify ball-racket contact. In forehand strokes angular velocities of internal arm rotation and adduction in shoulder joint correlated with racket velocity. Racket velocity was correlated with angular velocities (hip extension on the playing side; hip flexion on the opposite side; ankle flexion) in the case of a topspin forehand performed with maximal force –"heavy" topspin (FH3). In backhand strokes the velocities of arm abduction and shoulder girdle rotation towards the playing side correlated with racket velocity. The angular velocity of internal arm rotation and adduction in shoulder joint may be important components of a coordinated stroke, whilst angular velocity can substantially affect the racket speed when one is changing the type of stroke.

Key words: 3D motion analysis, biomechanics, sport, table tennis, topspin.

Introduction

In table tennis one's level depends on one's technical skills, such as ball hitting, setting up, proper footwork, but also on tactical, mental and motor skills. But table tennis is a sport in which the level of technical preparation is a crucial factor in high performance. Having high technical ability means that one is able to play using coordinated movements, with controlled power and able to impart adequate speed and spin to the ball. A high level of technical preparation involves perfect placement of the ball and being able to make the game almost unreadable to one's opponent. Analysing table tennis technique can help to identify the key factors underlying effective play (Zhang, et al. 2013). Most published biomechanical analyses of table tennis techniques have examined topspin strokes, especially the topspin forehand, viewed by many as the most frequent and effective stroke in the game in the last few decades (Iino and Kojima, 2011; Kondric et al., 2007; Neal, 1991; Yoshida et al., 1996; Zhang et al., 2013). Many publications on technical preparation of topspin strokes have been com-

parative analyses (Fu et al., 2016; Iino and Kojima, 2009, 2011; Kasai and Mori, 1998). Kasai and Mori (1998) emphasised that topspin technique varied with skill. Highly skilled players tended to use their whole body, rotating their upper body and using the knee joints effectively. Fu et al. (2016) investigated the characteristics of the centre of foot pressure trajectory during the table tennis topspin forehands. They detected that high-level players had better foot drive technique and better control of foot motion during the forehand loop. Iino and Kojima (2009) demonstrated the importance of racket acceleration and upper body rotation to performance of topspin strokes. The same researchers compared topspin forehand strokes in players of varying skill level and found that advanced players exhibited greater internal rotation and torque of the shoulder than intermediate players (Iino & Kojima, 2011). They also concluded that an increase in energy transfer may be an important factor in enabling intermediate players to generate a higher racket speed at impact when playing topspin forehands.

Only a few studies have explored the effect of certain factors on racket kinematics. Iino and Kojima (2015) investigated the effects of racket mass and stroke rate on the kinematics and kinetics of the trunk and the racket arm in the table tennis topspin backhand. They found, that the racket mass had no effect on the kinematic parameters of the trunk, playing arm that they examined and no effect on most of the kinetic parameters of the playing arm (the exception was that peak torque during wrist dorsiflexion increased with racket mass). Iino et al. (2008) evaluated the effect of movements in individual upper limb joints on racket velocity during performance of two variants of topspin backhand strokes and suggested that changes depend on the arrangement of individual upper limb segments rather than on angular velocities in individual joints of the limb holding the racket. Qian et al. (2016) investigated the role of lower limb kinematics in topspin forehands. They concluded that hip flexion and internal rotation were important, as well as the ability to using "lower limb drive". Bańkosz and Winiarski (2017, 2018) carried out extensive analysis of biomechanical and kinematic parameters in relation to topspin strokes, but it is difficult to find studies that offer comprehensive analysis of the relationship between the kinematics of individual body segments and racket kinematics. Racket kinematics, especially velocity of the racket when hitting the ball, are critical to the quality of the stroke. Increasing racket velocity at impact can affect the ball speed or rotation of

the ball (Neal, 1991). Determining the body segments, directions and ranges of movement and angular velocities that have a significant effect on racket velocity may be critical to improving training efficiency, especially in terms of movement technique. Changing the range or direction of movement, the angular velocity of a particular joint and, especially, racket velocity enables the player to change or adjust the parameters of the stroke, for example the angle, velocity and force of the stroke. Despite considerable effort by researchers and coaches, the rules of changing and adjusting movements during table tennis strokes are not fully understood. The aim of this study was, therefore, to calculate correlations between individual joints velocities and racket velocity (maximum velocity and velocity on impact with the ball) for variants of topspin forehand and backhand strokes in table tennis. The pattern of correlations should suggest how changes in body segment velocities influence racket velocity. Knowledge of such correlations may help coaches and players to improve topspin technique. We hypothesised that angular velocities of trunk and arm correlate with the resultant racket velocity because these segments propel the distal body segments. Based on the literature and our coaching experience, we assumed that the increase in the velocities of trunk rotation, knee extension and elbow flexion-extension are the primary contributors to racket velocity.

Methods

Participants

The study participants were 10 elite, female, junior table tennis players, numbered amongst the top 16 junior players in Poland. Their mean age was 16.0 years (± 2.5 y), and they had a mean body mass of 54.4 (± 3.2 kg) and mean body height of 1.65 (± 0.06 m). All players provided written, informed consent to participation in the study. The local ethics committee (the Senate Research Ethics Committee at the University School of Physical Education) approved the research.

The experiment was performed in certified biomechanical laboratory settings using a BTS Smart-E (BTS Bioengineering, Milan, Italy) motion analysis system. The system consisted of six digital cameras operating in the infrared spectrum (1.1μm) at a frequency of 120 Hz, in addition to two NetworkCam cameras operating in the visible range with a frequency of 20 Hz (Figure 1).

The data were collected through a digital USB/PC input and processed using the BTS Smart Analyser software. Thirty-four passive reflective markers were attached to the player's body with double-sided adhesive tape in specific locations featured in the biomechanical model. We used the human gait model for the lower extremities that was based on an extension of a published model (Davis et al., 1991) and an innovative model developed by us that includes additional points for the upper extremities (Figure 2): the acromion, lateral and medial epicondyle of the humerus, the styloid processes of the radius and ulna, and the head of the third metacarpal. The trunk segment was represented by the shoulder girdle (acromions and C7) and pelvic girdle (ASISs, greater and

lesser trochanters and sacral point - Pietraszewski et al., 2012). This arrangement enabled the use of a local reference system and determination of the centre of gravity for each segment: head, trunk and both lower and upper extremities (Teu et al., 2005). Furthermore, three markers were also placed on the edge of the racket. An acoustic sensor – a piezo-electric (PZT 5H) ceramic sound transducer - was also attached to the racket's surface to measure the exact time when the ball made contact with the racket. The racket was Donic Persson Powerplay with the 2.1mm rubber of Butterfly Tenergy 05. The marker and measurement protocol was pre-tested in a quasi-static simulation trial.
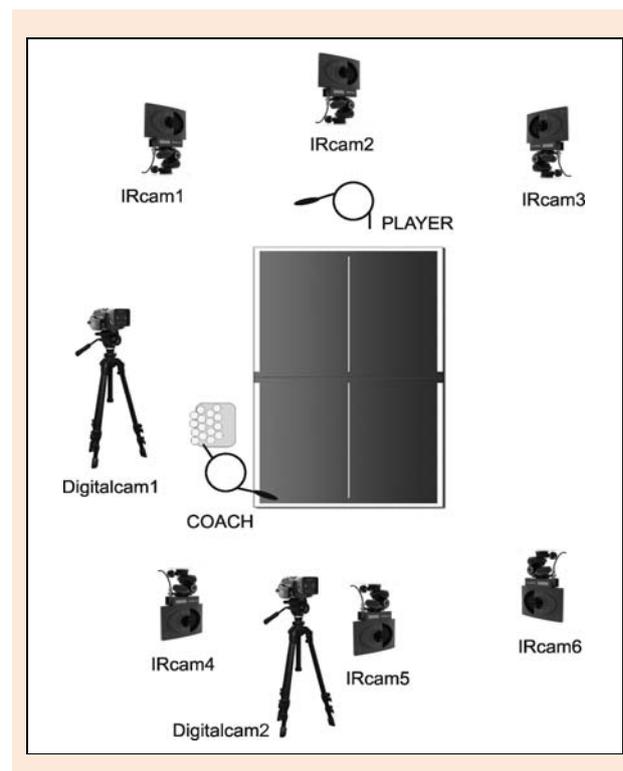
Figure 1. The measurement setup with a distribution of motion analysis system cameras. The system consisted of 6 IR cameras and 2 digital cameras.

Prior to the measurement procedure players followed standard (15-minute) and technical (20-minute) warm-up routines. Each player presented six tasks, three for forehand strokes and three for backhand strokes, with different levels of force and speed: FH1 (and BH1) - topspin forehand (and topspin backhand) against a no-spin ball, played with force, with a velocity and rotation of about 75%; FH2 (and BH2) - topspin forehands and topspin backhands against a backspin ball, played with force, with a velocity and rotation of around 75%; FH3 (and BH3) - topspin forehand (and topspin backhand) against a ball with no spin, played with force and with a velocity near to maximum for the stroke – "heavy topspin". The force of topspin strokes was estimated by the participants themselves, they were only asked to differentiate the power of the stroke. The task consisted of 15 strokes of the type specified. All balls were delivered to the player by the same person (coach) from a basket, one after another, at a fre-

quency of around 50 balls per minute. Right-handed players performed topspin strokes diagonally from the middle of the right and left sides of the table for forehands and backhands respectively. Racket displacements and the development of an acoustic signal in a cycle of strokes were used to identify the moment when the racket made contact with the ball and evaluate the maximum linear velocity of the racket (resultant - VRmax) and the linear velocity at the moment of contact (resultant - VRcont). Angular velocities in the joints involved in the forward phase of topspin strokes were also evaluated: the highest velocity in the joint (Vmax and Vmin, velocities of two opposite directions) and angular velocity at the moment of contact with the ball (Vcont). The angular velocities of following joints and directions of all limbs were calculated:

wrist joint (W): for abduction – adduction (AA) and flexion – extension (FE), elbow joint (E): FE and pronation-supination (PS), shoulder joint (Sh): FE, internal – external rotation (IE) and AA, ankle joint (A): FE, knee joint (K): FE, hip joint (H): FE, IE and AA.

We also measured the spatial orientation of the pelvis (P) and shoulder girdle (S): obliquity (Obli), tilt (Tilt) and rotation (Rot). The directions of individual movements are represented by the sign of the velocity. Negative velocities represent extension, adduction and internal rotation. In the case of the trunk and pelvic girdle negative velocities represent body bend to the right, rotation to the right and backward body bend. Positive velocities represent bending, abduction and external rotation. In the case of body trunk and pelvic girdle positive signs represent body bend to the left, rotation to the left and forward body bend.

The velocities were calculated for each test. Further analysis focused on these values and the specific linear velocities of the racket i.e. VRmax, VRcont. The linear velocities of the racket were established by determining the resultant linear velocity of the marker on the tip of the racket (the middle marker from three attached to the racket), the other two markers were to determine racket plane orientation.

Statistical analysis

Data from all the players were submitted to further analysis. The basic descriptive statistics (arithmetic means and standard deviations) were evaluated. The Shapiro-Wilk test was used to test the normality of data distribution.

Multiple regression analysis (MRA) was employed using the best subset regression method and sigma-restricted parameterization. The R squared and standardised regression coefficients for each sub-model tested and the best possible subset of five variables were selected to describe VRmax and VRcont variables characterized by means of the regression coefficient. MRA was used to determine which of the independent variables (angular velocities in the joints) provided the best description of the dependent variable (VRmax and VRcont). In regression methodology the dependent variable Y is related to predictors (Xi) according to the mean function: $Y = \alpha + b_i \cdot X_i + \varepsilon$, where α is the intercept, b_i are the coefficients of regression for the i-predictor and ε is the standard error of the estimation. The squared multiple correlation of the model (R^2) indicates the percentage of variance in Y explained by the model.
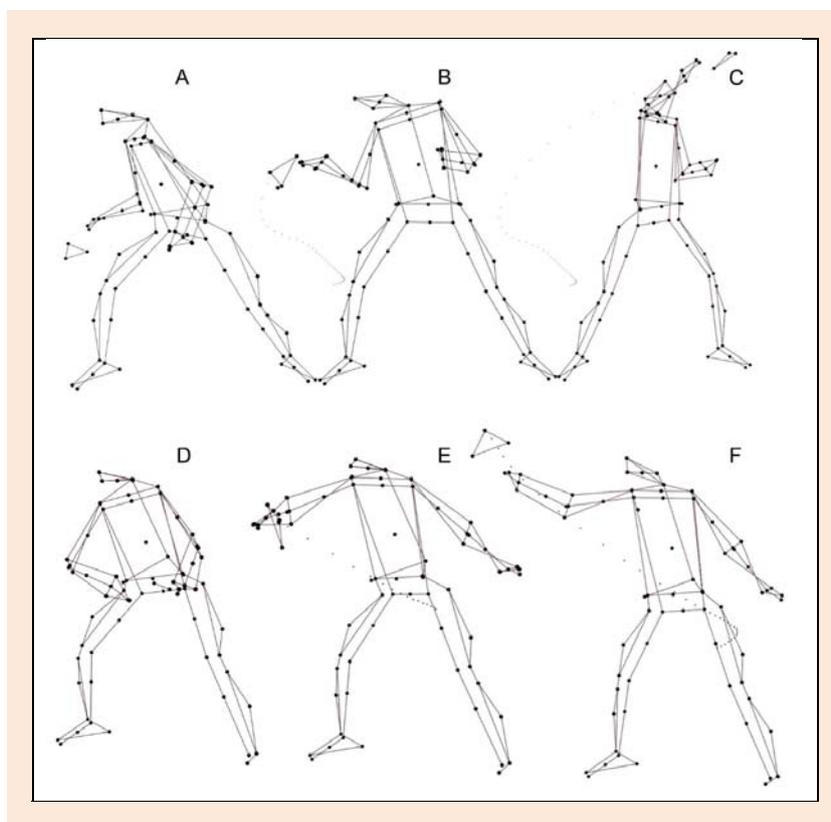
Figure 2. Experimental model with specified key events: beginning of the movement (A & D), contact between racket and the ball (B & E) termination of the movement (C & F) for topspin forehand (upper) and topspin backhand (bottom).

Table 1. Values of arithmetic means (Mean) and standard deviations (SD) for racket velocity (m/s) and time of reaching the velocity (s) in all tests. Data are means (±SD).

	FH1	FH2	FH3	BH1	BH2	BH3
VRmax	13.13(1.14)	14.63(1.08)	14.69(1.45)	12.55(2.05)	14.09(1.32)	13.60(2.40)
VRcont	13.03(1.19)	14.53(1.04)	14.55(1.46)	11.63(1.99)	13.02(1.42)	12.64(2.27)
tVRmax	0.14(0.02)	0.16(0.03)	0.15(0.03)	0.14(0.03)	0.15(0.03)	0.13(0.03)
tVRcont	0.13(0.02)	0.15(0.03)	0.15(0.03)	0.13(0.02)	0.14(0.03)	0.12(0.02)

VRmax - maximal racket velocity; VRcont - velocity of the racket at the moment of contact with the ball; tVRmax - time of reaching maximal velocity; tVRcont – time in the moment of contact; FH1, FH2, FH3, BH1, BH2, BH3 - individual tests

Table 2. Values of arithmetic means (Mean) and standard deviations (SD) of angular maximal velocities in joints (Vmax) for individual tests (degree/s). Data are means (±SD).

	FH1	FH2	FH3	BH1	BH2	BH3
VmaxRAFE	78.10(49.98)	84.53(56.61)	89.00(42.56)*†	98.59(77.46)	118.75(87.02)	126.73(98.32)
VmaxLAFE	183.02(106.19)	184.59(86.63)	191.62(104.04)	72.58(49.79)	65.81(50.11)	97.70(68.31)*†
VmaxRKFE	87.00(60.28)†	83.30(67.35)	116.80(78.46)	28.14(62.95)	35.83(74.82)	52.49(82.76)
VmaxLKFE	93.10(77.30)	138.35(118.38)	125.17(120.43)	83.17(73.93)	65.32(78.03)†	123.71(90.76)
VmaxRHAA	67.96(31.65)	115.05(113.91)	89.26(52.72)	113.89(72.01)	141.47(91.74)	148.73(94.20)
VmaxLHAA	128.87(39.64)	140.77(120.43)	162.27(49.76)	78.52(50.60)	99.94(78.23)*†	98.61(63.22)
VmaxRHFE	42.22(66.20)	66.53(88.57)	92.60(111.46)*	32.45(62.35)	33.25(69.98)	63.73(82.90)
VmaxLHFE	200.50(94.05)	185.92(100.48)	225.81(113.27)†	55.03(66.64)	22.53(84.09)	72.10(74.36)
VmaxRHIE	163.43(92.78)†	162.82(97.05)	197.48(128.18)	97.24(70.94)	119.65(106.21)	132.11(88.73)
VmaxLHIE	207.97(86.06)	240.12(145.44)	274.23(96.29)	99.95(64.65)	122.15(96.53)	143.95(118.56)
VmaxPRot	320.63(95.27)	312.21(145.29)	392.45(132.87)	81.72(58.40)	90.31(59.61)	136.16(142.21)
VmaxPTilt	64.46(29.78)	76.04(28.78)	84.88(50.32)	31.84(29.69)	31.52(27.97)*	46.18(48.26)
VmaxPObli	40.70(26.26)†	60.85(25.74)	50.14(31.88)	61.51(38.09)	85.55(50.46)	103.83(74.00)
VmaxSRot	513.31(97.36)	520.62(232.83)	579.01(154.14)	114.52(76.21)	145.15(70.65)	129.49(67.50)
VmaxSTilt	77.16(62.10)	90.01(71.09)	110.31(92.86)	43.45(62.36)	46.23(64.35)	48.37(71.56
VmaxSObli	129.9253.07)	204.48(79.48)	195.23(117.82)	126.83(56.00)	147.55(65.69)	157.19(123.25)
VmaxRShFE	439.85(113.92)	472.70(135.31)	443.13(94.96)	292.14(58.32)	302.85(84.77)	292.62(115.28)
VmaxRShAA	97.95(60.36)*	138.66(69.77)	127.71(47.03)	192.52(149.95)*†	254.36(128.33)*†	273.53(159.11)*†
VmaxRShIE	247.79(136.32)	437.11(272.46)	461.95(351.75)	778.69(255.99)	955.02(182.66)	878.27(305.78)*
VmaxREPS	209.11(87.68)	273.93(179.27)	233.79(128.99)	335.71(113.27)	370.58(132.35)	354.02(146.06)
VmaxREFE	291.43(94.58)	324.18(106.01)	299.66(100.95)	204.85(83.47)	189.77(70.15)	263.02(134.49)
VmaxRWAA	167.39(133.63)	203.67(336.00)	163.89(97.82)	160.36(121.47)	221.85(95.55)	187.99(106.58)
VmaxRWIE	134.03(173.32)	97.27(79.04)	108.32(50.74)	148.21(67.88)	172.06(232.77)	156.91(95.65)
VmaxRWFE	224.21(162.12)	225.77(157.89)	227.53(99.36)	268.53(160.93)	363.80(187.67)	386.99(335.14)
VmaxLWFE	285.24(336.42)	409.50(112.56)	247.37(172.53)	201.46(120.63)	298.60(369.36)	262.74(585.79)
VmaxLWIE	134.75(111.82)	195.79(249.25)	156.41(143.73)	89.75(122.22)	133.53(95.25)	141.88(153.40)
VmaxLWAA	168.60(212.09)	182.80(173.94)	110.17(62.91)	109.81(72.55)	109.34(87.12)	101.30(149.01)
VmaxLEFE	389.61(207.92)	409.50(112.56)	398.96(145.37)	152.83(96.95)*	130.33(72.83)	167.9(90.35)
VmaxLEPS	710.78(129.73)	289.60(196.46)	254.51(139.52)	153.89(176.83)	218.22(143.26)	172.22(124.40)
VmaxLShFE	389.61(207.92)	314.83(115.42)	345.02(128.62)	27.31(88.49)	67.30(64.61)	40.04(63.03)†
VmaxLShAA	263.78(165.06)	296.05(162.82)	342.07(187.19)	381.41(167.57)	348.89(190.65)	410.35(215.36)
VmaxLShIE	499.61(257.51)	635.31(269.36)	506.57(267.37)	272.780(166.58)	241.18(135.00)	256.99(175.25)

* - the value of velocity, which correlates to VRmax. † - the value of velocity, which correlates to VRcont.
Wrist joint (W): abduction (AA) and flexion (FE), elbow joint (E): flexion (FE) and internal rotation –pronation (IE), shoulder joint (Sh): flexion (FE), internal rotation (IE) and abduction (AA), ankle joint (A): flexion (FE), knee joint (K): flexion (FE), hip joint (H): flexion (FE), internal rotation (IE) and abduction (AA), pelvis (P) - obliquity (Obli), tilt (Tilt) and rotation (Rot), and shoulder girdle (S) obliquity (Obli), tilt (Tilt) and rotation (Rot).

Results

Values of arithmetic means and standard deviations for racket velocity (VRmax, VRcont) and time of reaching the velocity in all tests are presented in Table 1. In forehand strokes VRmax was similar to VRcont; in the case of backhand strokes VRmax and VRcont were also similar, although the arithmetic mean for VRmax was higher than that for VRcont.

Maximal angular velocities during topspin forehand and backhand in selected joints are presented in Table 2. In forehand strokes high values of maximal angular velocity were recorded for shoulders rotation towards the non-playing side (VmaxSRot), the highest for FH3. In backhand strokes the highest angular velocity was recorded for external rotation in the shoulder joint (VmaxRShIE).
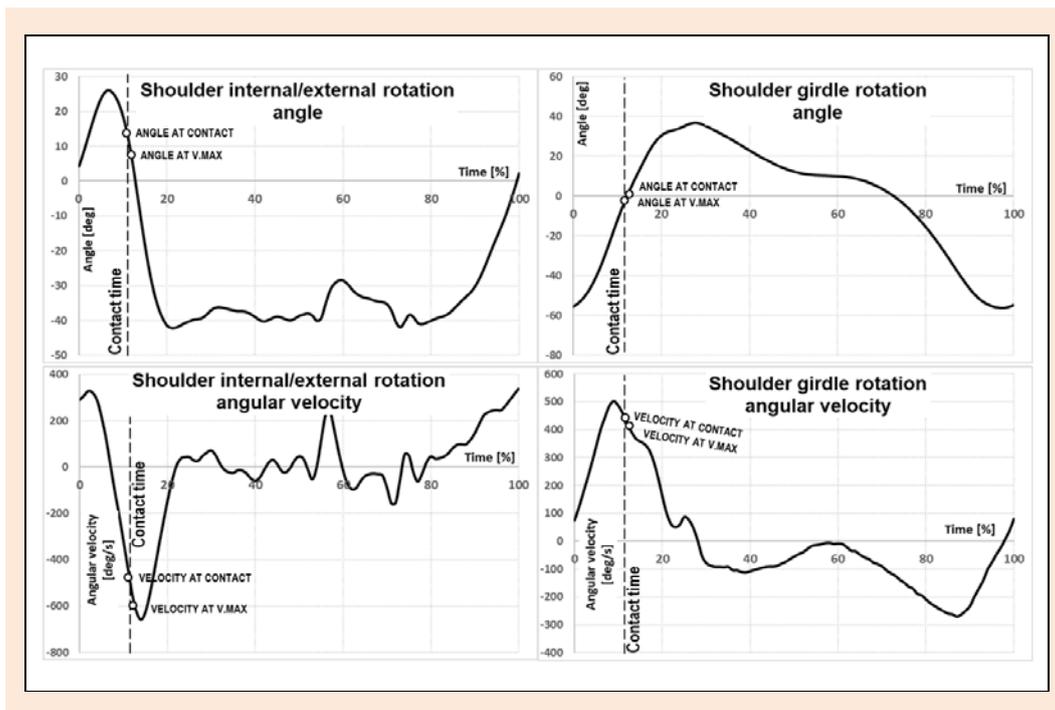
Values of Vmin - arithmetic means and standard deviations of the highest angular velocities in joints turned in opposite directions to Vmax in individual tests are presented in Table 3. Vmin values, i.e. the largest angular velocities in individual joints performing the opposite of the movements responsible for the above-mentioned maximal velocities, were very varied (Table 3).

The highest arithmetic mean of angular velocities in the joints at the moment of contact were observed in internal rotation in the shoulder joint (VcontRShIE) in topspin backhands and extension of the shoulder (VcontRShFE) in topspin forehands. The example of the values of VRmax and VRcont and changes of angles and angular velocities during forehand topspin are presented in Figure 3. Standard deviations for movements in most joints were fairly high.

Table 3. Values of arithmetic means (Mean) and standard deviations (SD) of the highest angular velocities in joints turned in opposite directions to Vmax (Vmin) in individual tests (degree/s). Data are means (±SD).

	FH1	FH2	FH3	BH1	BH2	BH3
VminRAFE	-30.18(55.08)*	-98.00(164.50)	-84.22(48.04)	-41.69(49.50)	-51.44(53.33)	-46.87(46.58)
VminLAFE	-42.46(34.05)	-109.31(76.40)	-126.89(74.55)	-82.73(43.06)	-84.76(45.83)	-78.26(29.28)
VminRKFE	-77.03(29.97)	-174.25(145.72)	-172.93(106.34)	-170.63(49.73)	-184.21(53.03)	-193.40(84.38)
VminLKFE	-102.81(35.74)	-170.23(76.37)	-147.17(62.48)	-171.65(66.15)	-145.57(80.55)	-159.44(74.27)
VminRHAA	-223.96(164.2)	-193.86(56.91)	-198.41(42.92)	-64.27(50.77)	-77.29(98.19)*†	-103.44(70.72)
VminLHAA	-282.35(254.36)	-87.16(61.6)	-81.32(55.69)	-93.70(63.78)	-118.24(86.85)	-121.75(74.66)*†
VminRHFE	-152.61(216.04)*†	-356.00(112.6)	-378.64(128.33)†	-147.52(80.16)	-193.60(71.86)	-174.96(71.52)
VminLHFE	-114.28(77.55)	-120.67(140.87)	-49.52(54.71)*	-202.39(85.48)*	-240.87(116.00)	-200.30(100.74)
VminRHIE	-152.88(171.88)	-254.66(137)	-290.62(153.70)	-151.45(81.81)	-175.61(84.31)	-183.61(92.98)
VminLHIE	-182.87(332.38)	-259.41(134.1)3	-209.86(89.40)	-123.52(71.30)	-164.85(114.01)	-138.27(105.97)
VminPRot	-113.8(83.45)	-15.10(138.4)2	-26.75(76.99)	-130.92(63.80)	-156.77(80.35)	-182.87(96.11)
VminPTilt	-77.91(58.73)	-141.69(41.04)2	-111.97(32.20)	-61.24(32.91)	-113.95(186.56)	-72.43(50.94)
VminPObli	-148.60(57.76)	-76.42(44.36)	-78.57(27.89)	-43.93(29.07)	-62.82(80.99)	-60.32(46.84)
VminSRot	-282.35(254.36)	-4.77(175.79)	-2.46(148.3)	-116.48(77.88)	-163.92(82.15)	-166.24(92.11)
VminSTilt	-114.28(77.55)	-394.15(95.72)	-372.14(87.73)	-194.07(67.03)	-229.57(76.93)	-228.96(111.97)
VminSObli	-182.87(332.38)†	-220.83(81.16)	-200.62(86.57)	-50.59(42.31)	-58.77(40.28)	-96.99(124.81)
VminRShFE	-82.13(130.16)	-194.75101.81)	-175.32(155.67)	-140.17(65.16)	-135.87(73.63)	-150.93(84.58)
VminRShAA	-189.75(39.49)	-238.3791.18)	-199.60(106.16)	-129.50(62.57)	-165.17(60.65)	-84.41(144.26)
VminRShIE	-42.16(65.23)	-571.84(256.79)	-702.22(252.69)	-177.61(243.90)	-337.97(288.03)	-222.62(178.89)*†
VminREFE	-42.16(65.23)	-76.66(72.484)	-87.90(85.23)	-618.90(183.48)	-457.24(150.77)	-708.64(204.65)
VminREPS	-42.46(34.05)	-271.70(242.52)	-332.32(156.66)	-711.89(207.26)	-871.79(207.60)	-696.80(210.13)
VminRWAA	-312.15(67.11)	-174.69(241.97)	-221.97(171.91)	-328.28(151.33)	-308.66(170.13)	-402.79(227.61)
VminRWIE	-170.87(45.64)	-84.01(68.45)	-110.67(90.60)	-134.05(89.59)	-171.53(120.87)	-227.99(373.79)
VminRWFE	-188.29(93.94)	-231.76(155.48)	-223.98(81.74)	-992.84(207.09)	-1054.11(290.23)	-1117.42(347.53)
VminLWFE	-282.35(254.36)	-232.93(135.33)	-325.84(333.17)	-462.97(150.33)	-220.31(144.03)	-201.21(126.54)
VminLWIE	-182.87(332.38)	-201.06(270.99)	-134.56(95.63)	-127.43(175.31)	-132.45(92.92)	-156.7(129.14)
VminLWAA	-114.28(77.55)	-165.88(182.36)	-152.82(131.23)	-89.14(104.28)	-141.08(105.63)	-134.09(128.46)
VminLEFE	-82.13(130.16)	-89.40(155.80)	-76.15(152.40)	-309.19(245.07)	-227.19(118.74)	-290.00(247.82)
VminLEPS	-635.55(354.49)	-244.66(180.32)	-260.92(128.01)	-292.04(170.13)	-284.84(151.81)	-266.14(175.10)
VminLShFE	-233.19(149.47)	-389.32(306.25)*†	-256.51(59.13)	-208.38(115.97)	-214.63(135.85)	-228.74(157.94)
VminLShAA	-408.95(181.03)	-538.62(260.99)	-476.91(213.49)	-74.05(88.22)†	-151.13(86.31)	-168.52(188.83)
VminLShIE	-262.39(132.73)	-321.65(188.63)	-336.63(176.04)	-168.02(113.93)	-204.25(131.65)	-184.96(111.81)

*- the value of velocity, which correlates to VRmax. † - the value of velocity, which correlates to VRcont

Wrist joint (W): abduction (AA) and flexion (FE), elbow joint (E): flexion (FE) and internal rotation –pronation (IE), shoulder joint (Sh): flexion (FE), internal rotation (IE) and abduction (AA), ankle joint (A): flexion (FE), knee joint (K): flexion (FE), hip joint (H): flexion (FE), internal rotation (IE) and abduction (AA), pelvis (P) - obliquity (Obli), tilt (Tilt) and rotation (Rot), and shoulder girdle (S) obliquity (Obli), tilt (Tilt) and rotation (Rot).

Figure 3. Changes in angles and angular velocity in shoulder internal rotation and shoulder girdle rotation during topspin forehand (FH1) – an example averaged over 5 trials, right-handed player

Table 4. Values of arithmetic means (Mean) and standard deviations (SD) of angular velocities in joints at the moment of contact of the racket with the ball (Vcont) in individual tests (degree/s). Data are means (±SD).

	FH1	FH2	FH3	BH1	BH2	BH3
VcontRAFE	15.62(54.13)	-4.63(54.27)	7.54(52.22)	63.00(73.94)	45.29(63.34)	65.27(97.17)
VcontLAFE	49.65(113.4)	43.93(105.88)	50.21(102.13)	14.70(62.22)	-10.75(58.94)	7.65(47.96)
VcontRKFE	-37.97(80.97)	-46.10(100.95)	-17.76(138.26)	-104.38(73.43)	-106.54(73.82)	-106.85(80.67)
VcontLKFE	-31.65(76.69)	-20.95(109.07)	2.42(90.91)	-19.65(96.38)	-11.37(91.76)	4.04(86.26)
VcontRHAA	-32.17(69.91)	-27.79(66.92)*†	-27.73(70.53)	68.28(71.40)	93.29(77.13)	103.59(99.55)
VcontLHAA	45.21(60.45)	15.1665.80)	67.48(72.87)	-45.52(72.27)	-72.42(79.76)	-76.93(82.42)
VcontRHFE	-198.41(110.29)	-206.74(155.02)	-237.03(127.49)	-30.21(70.87)	-53.95(83.46)	-16.82(89.43)
VcontLHFE	79.34(106.97)	5.26(188.00)	103.71(110.37)	-87.31(103.79)	-138.68(88.43)	-107.45(118.86)
VcontRHIE	-93.00(158.11)	-135.05(159.22)	-131.98(183.8)	36.93(62.85)	30.68(62.44)	79.47(94.71)
VcontLHIE	-68.69(141.27)	-154.74(183.50)	-92.07(153.00)	-43.65(73.81)	-59.90(82.20)	-34.54(95.86)
VcontPRot	218.90(122.41)	160.42(208.77)	248.39(132.84)	-88.45(67.69)	-113.43(78.74)	-139.18(92.55)
VcontPTilt	-53.48(38.87)*	-81.37(53.66)	-67.57(43.17)	-1.86(38.65)	-19.10(37.68)	-2.56(38.81)
VcontPObli	-18.41(40.20)	-20.63(46.34)	-6.02(40.26)	31.03(47.32)	40.9048.05)	56.22(62.90)
VcontSRot	397.03(126.73)	321.68(251.92)	403.79(221.86)	-35.79(111.00)*†	-98.50(119.23)	-77.38(158.93)
VcontSTilt	-241.14(75.89)	-326.42(85.68)	-302.32(92.97)	-79.45(79.44)	-99.44(85.62)	-71.77(116.26)
VcontSObli	60.41(62.00)	100.53(105.12)	93.03(100.57)	37.97(59.34)	61.04(58.86)	53.17(76.25)
VcontRShFE	246.21(320.34)	285.26(384.53)	348.55(79.02)	188.48(86.37)†	185.43(117.01)	199.48(145.04)
VcontRShAA	-43.55(90.03)	-23.16(128.49)†	26.50(85.09)	8.48(69.39)†	-54.01(77.94)	46.69(131.23)
VcontRShIE	-219.10(550.35)*	-264.00(608.23)*†	-328.12(636.71)*†	608.79(216.59)	745.04(190.53)	541.34(238.24)
VcontREPS	-89.85(97.67)	-43.58(136.77)	-155.84(123.83)	-533.69(222.36)	-724.15(202.57)†	-410.71(216.75)
VcontREFE	40.96(87.01)	43.37(75.67)	-21.64(142.22)	-468.93(141.41)	-301.06(122.47)*	-512.85(157.310
VcontRWAA	29.23(46.77)	54.84(94.35)	6.10(129.03)	-260.59(138.38)	-206.86(127.00)	-256.93(156.73)
VcontRWIE	-15.94(89.48)	17.91(31.48)	3.29(59.82)	48.83(96.39)*	27.05(108.31)	15.54(134.13)
VcontRWFE	64.07(92.56)	37.47(101.77)	50.76(128.42)	-790.34(537.74)	-915.64(311.59)	-989.48(346.11)
VcontLWFE	-2.45(183.80)	-11.32(139.52)	33.83(165.49)	31.03(47.32)	-31.89(161.30)	-11.38(156.00)
VcontLWIE	-10.99(67.40)	15.16(62.71)	6.15(74.60)	1.57(109.50)	17.04(96.48)	-0.26(73.350
VcontLWAA	10.03(81.16)	4.83(115.08)	4.23(70.90)	-7.15(38.03)	-10.48(118.46)	-65.20(190.18)
VcontLEFE	214.85(192.89)	195.69(177.53)	188.22(253.69)	16.71(157.73)	-49.82(124.18)	-35.17(143.23)
VcontLEPS	176.28(779.83)	43.00(145.11)	-30.57(116.09)	-158.42(181.83)	-42.26(149.89)	-73.16(183.40)
VcontLShFE	124.24(242.43)	117.26(329.83)	291.55(135.66)	-137.69(132.47)	-116.48(156.43)	-126.00(184.87)
VcontLShAA	-68.07(203.14)	-74.11(166.36)*	-138.25(122.98)*†	276.65(164.53)	228.26(212.94)	240.03(219.19)
VcontLShIE	166.86(461.56)	72.14(283.33)*†	89.99(253.37)	75.80(164.19)	88.49(147.90)	106.95(161.75)

* - the value of velocity, which correlates to VRmax. † - the value of velocity, which correlates to VRcont
Wrist joint (W): abduction – adduction (AA) and flexion – extension (FE), elbow joint (E): flexion-extension (FE) and pronation-supination (PS), shoulder joint (Sh): flexion – extension (FE), internal – external rotation (IE) and abduction – adduction (AA), ankle joint (A): flexion – extension (FE), knee joint (K): flexion-extension (FE), hip joint (H): flexion – extension (FE), internal – external rotation (IE) and abduction – adduction (AA), pelvis (P) - obliquity (Obli), tilt (Tilt) and rotation (Rot), and shoulder girdle (S) obliquity (Obli), tilt (Tilt) and rotation (Rot). Minus sign – extension, adduction or external rotation; plus sign – flexion, abduction or internal rotation

Best subset multiple regression revealed the types and directions of movements responsible for the maximal velocities or velocities at the moment of contact (Vmax, Vmin, Vcont) significantly correlated with VRmax and VRcont. All values of angular velocities which were correlated with VRmax or VRcont are marked in Tables 2, 3 and 4. Chosen results of best subset multiple regression are presented in Table 5. β coefficients were used to infer the identity of the parameter most substantially correlated with racket velocity and the highest values were observed in forehand strokes, in relations to the angular velocity at impact for the internal rotation of the playing hand VcontRShIE. This parameter (VcontRShIE) was included in the regression model (which means the occurrence of correlation) in the case of tests FH1, FH2 and FH3 in correlation with VRmax and for FH2 and FH3 in correlation with VRcont. The negative sign of β coefficients results from negative sign of Vcont. The frequent parameter of forehand strokes included in the model was VminRHFE (hip joint extension movement), which was observed in FH1 and FH3, both with respect to VRmax and VRcont (Table 5). Angular velocity at the moment of contact with the ball during shoulder adduction (VcontRShAA) was observed twice in the FH2 tests with respect to VRmax and VRcont (Table 5). In the case of the backhand strokes, it was demonstrated that the maximal angular velocity during shoulder joint abduction (VmaxRShAA) was correlated with VRmax and VRcont in all tests, with the strongest correlation being BH2 with respect to VRmax and BH1 with respect to VRcont (Tab. 5). Similarly, other values of angular velocities occurred twice in the regression model (for VRmax and VRcont): VcontSRot (velocity at the moment of contact in shoulder girdle rotation towards the playing side) was found in BH1, VmaxLHAA (V max during left hip abduction) in BH2 and VminLHAA (Vmin during left hip adduction) in BH3 (Table 5).

The coefficient of determination (R^2), which suggests the strength of the relationship, was ca. 0.8 in most cases, reflecting relatively strong correlations between the variables in the individual models. The strongest relationship was observed in the FH3 test for correlations of angular velocities with VRmax and VRcont (Table 5). The lowest values for the R^2 coefficient were observed in BH2 for correlations between angular velocities and VRcont and VRmax . In all correlations the standard errors were very small, similar to the coefficient p (Table 5).

Table 5. Chosen results of the best subset multiple regression methodology.

		VRmax					**VRcont**		
Sample	**R²**	**Xᵢ**	**p**	**β**	**Sample**	**R²**	**Xᵢ**	**p**	**β**
FH1	0.794				**FH1**	0.763			
		VcontPTilt	0.000	-0.245			**VmaxRKFE**	0.000	-0.373
		VcontRShIE	0.000	-0.535			**VmaxRHIE**	0.000	-0.296
		VmaxRShAA	0.000	0.376			**VmaxPObli**	0.000	0.293
		VminRHFE	0.000	-0.434			**VminSObli**	0.000	-0.553
		VminRAFE	0.000	0.486			**VminRHFE**	0.000	-0.622
FH2	0.803				**FH2**	0.818			
		VcontRHAA	0.000	-0.296			**VcontRHAA**	0.000	-0.291
		VcontLShIE	0.000	0.851			**VcontLShIE**	0.000	0.800
		VcontRShAA	0.000	-0.449			**VcontRShAA**	0.000	-0.390
		VcontRShIE	0.000	-1.372			**VcontRShIE**	0.000	-1.398
		VminLShFE	0.000	-1.003			**VminLShFE**	0.000	-1.088
FH3	0.905				**FH3**	0.892			
		VcontLShAA	0.000	-0.274			**VcontLShAA**	0.000	-0.266
		VcontRShIE	0.000	-0.816			**VcontRShIE**	0.000	-0.781
		VmaxLHFE	0.000	-0.312			**VmaxLHFE**	0.000	-0.284
		VmaxRAFE	0.000	-0.234			**VmaxRAFE**	0.000	-0.240
		VminRHFE	0.000	-0.498			**VminRHFE**	0.000	-0.511
BH1	0.833				**BH1**	0.755			
		VcontRWIE	0.000	0.417			**VcontSRot**	0.000	-0.447
		VcontSRot	0.000	-0.540			**VcontRShFE**	0.000	-0.261
		VmaxRShAA	0.000	0.584			**VcontRShAA**	0.000	0.440
		VmaxLEFE	0.001	-0.152			**VmaxRShAA**	0.000	0.817
		VminLHFE	0.000	-0.308			**VminLShAA**	0.002	0.203
BH2	0.666				**BH2**	0.465			
		VcontREFE	0.000	0.295			VcontREIE	0.001	-0.253
		VmaxLHAA	0.000	0.599			VmaxLHAA	0.000	0.457
		VmaxPTilt	0.000	-0.347			VmaxLKFE	0.001	-0.277
		VmaxRShAA	0.000	0.701			VmaxRShAA	0.000	0.486
		VminRHAA	0.000	0.327			VminRHAA	0.005	0.296
BH3	0.816				**BH3**	0.744			
		VmaxLAFEm	0.000	0.288			VmaxLAFE	0.000	0.224
		VmaxRShIE	0.000	0.237			VmaxRShAA	0.000	0.511
		VmaxRShAA	0.000	0.433			VmaxLShFE	0.000	-0.258
		VminRShIE	0.000	-0.223			VminRShIE	0.000	-0.349
		VminLHAA	0.000	-0.402			VminLHAA	0.000	-0.418

In used regression methodology (Y) is related to predictors (Xᵢ) according to the mean function: $Y = \alpha + b_i \cdot X_i + \varepsilon$, where alfa is the intercept, b_i are the coefficients of regression for the i-predictor and β is the standard error of the estimation. The squared multiple correlation of the model (R^2) explains % of the variability of the data. p - the level of significance, β= the beta correlation coefficient.

Discussion

The aim of our tests was to uncover correlations between angular velocities recorded in individual joints and body segments and the racket velocity in several variants of topspin strokes. The results lead to the conclusion that maximal velocities and velocities at impact are very similar, although in all tests the mean velocities at impact were slightly lower than maximal velocities, presumably because contact between racket and ball occurs slightly before maximal racket velocity is reached. It is likely that the racket reaches maximal velocity immediately after the first contact, but still with the ball remaining "at the racket". We propose that prolonged contact between racket and ball during acceleration increases rotation due to the effects of friction (Lufang et al., 2013). This could be confirmed by using higher frequencies in the motion analysis system.

The best subset multiple regression used in the study demonstrated that angular velocity at impact during internal rotation of the shoulder joint (VcontShIE) is strongly correlated with VRmax and VRcont during top-

spin forehand strokes. It seems likely that in table tennis internal rotation of the arm in shoulder joint plays an important role in coordination of forehand stroke. Increases in the angular velocity of internal rotation of the arm accompany increases in racket velocity. It is also possible, that the rapid internal shoulder rotation helps to control the ball by ensuring that the ball is "covered" by the racket and extending the duration of contact between racket and ball. Iino and Kojima (2011) emphasized the importance of internal rotation to coordination of forehand strokes in table tennis; they found that advanced players could exert greater torque during internal rotation of the shoulder than intermediate players. The same researchers pointed out that internal rotation of the shoulder contributed substantially to the racket speed at impact (Iino and Kojima, 2009). Researcher in similar sports, such as tennis, have also emphasized the significance of internal rotation (Fleisig et al., 2003; Marshall and Elliott, 2000; Tanabe and Ito 2007). Another finding of our study is that the velocity of shoulder adduction (VcontRShAA) was fairly strongly correlated with racket velocities in FH2. In this test players hit topspin

strokes after delivery of a ball with backspin, so greater involvement of the arm adductors at the moment of contact with the ball was required, followed by the adduction movement with shoulder flexion and then changing to abduction in this joint (in the follow-through phase). In four tests, racket velocity was correlated with VminRHFE, i.e. the highest velocity during right hip extension, which presumably increased the upward movement component, as right hip adduction did in the FH2 test (angular velocity in VcontRHAA was also correlated with racket velocities).

The presence of angular velocities from the non-dominant upper limb (VcontLShIE, VminLShFE) in the calculation model (especially in FH2) is interesting and may be due to extension of the non-dominant hand arm and internal rotation of the non-dominant shoulder during the stroke to ensure balance.

In the FH3 test we found correlations with racket velocities in the cases of VmaxLHFE (maximal velocity of left hip joint flexion), the previously mentioned VminRHFE (maximal velocity of right hip joint extension) and VmaxRAFE (maximal velocity of ankle joint flexion), probably connected with the greater contribution of the transfer of the centre of gravity from the lower limb on the playing side towards the limb on the non-playing side and right hip extension (connected with unloading this limb).

Analysis of the correlations of angular velocities in joints and body segments with racket velocities during backhand strokes revealed the specific role of the VmaxRShAA parameter (maximal velocity of the abduction movement in the shoulder joint) in all variants of topspin strokes. Motion of abduction/adduction, driven by rotation of the shoulder girdle towards the playing side (VcontSRot was correlated with racket velocity in two of the tasks) probably influences racket velocity (Table 5). Iino et al. (2008) evaluated the effect of elbow and wrist movements on racket velocity for two variants of topspin backhand. They found that elbow extension affected the forward velocity of the racket and dorsal flexion the upward velocity. Iino and Kojima (2016) also found that the mechanical energy of the racket at ball impact in topspin backhands was mainly transferred by the force and torque of the shoulder. Undoubtedly, according to the principles of proximal-to-distal sequencing and summation of speed, all movements of the elbow, wrist and shoulder when appropriately coordinated influence racket velocity. In our study we found that the movements whose velocities were correlated with racket velocity (arm abduction and shoulder girdle rotation) were those that propelled the more distal segments of the playing limb.

It should be stressed that the coefficients R^2 and β were lower for backhand strokes than forehand strokes, suggesting lower correlations. This is likely to have been caused by the participants' less frequent use of backhand strokes than forehand strokes, which was due to their varied playing styles and, consequently, varied techniques.

However, during forehand strokes the highest values of angular velocities were found for angular velocity of shoulder girdle rotation towards the non-playing side. These patterns of movements and velocities corroborate published studies. Iino and Kojima (2009) found that trunk rotation contributed substantially to racket velocity during topspin forehand strokes. Qian et al. (2016) examined the importance of lower limb joint movements during performance of powerful topspin forehands and found that advanced table tennis players displayed a greater range of hip flexion and external knee joint rotation at the end of the swing phase than less advanced players. They also stressed that advanced players displayed a greater range of hip rotation and hip extension, as well as greater velocities of dorsal and plantar ankle flexion and hip rotation in the forward phase. We were unable to confirm these latter findings, perhaps due to the high variation in angular velocities in our sample. This variation is probably due to the varied techniques used by our sample. This phenomenon is common in table tennis, which is a very complex and varied game in terms of both technique and tactics, as demonstrated previously (Bańkosz and Winiarski, 2017; Munivrana et al. 2015). During table tennis strokes a lack of movement in certain joints can certainly be compensated for by movement in other body segments. The variation in technique can be considered a limitation of our assessments and leads us to conclude that in table tennis the best approach to be modelling movements would be case studies of a small number of champions.

It should also be emphasized that the correlations reported here relate the resultant racket velocities. Although separating the three directional components (upward, forward, lateral) would make it easier to detect additional correlations it would increase the already high number of parameters analysed.

The results obtained in this study can be used directly in training of both female and male table tennis players. Coordination of topspin forehand and backhand strokes should improve if emphasis is placed on optimising the range and velocity of the movements listed in the study, as this should help to increase racket velocity.

Maximal racket velocity and velocity at contact with the ball were very similar, with non-significant differences in the magnitude and time taken to reach these values resulting from acceleration of the racket at the moment of contact with the ball, which is used to increase ball rotation.

Conclusions

In forehand strokes, in particular angular velocity of internal arm rotation and shoulder joint adduction at the moment of contact were both correlated with racket velocity. In the case of topspin forehand strokes performed with maximal force (FH3) racket velocity was also correlated with the angular velocities of playing- and non-playing-side hip extension and ankle flexion. These movements may be important components of a coordinated stroke, such that their angular velocity substantially affects racket speed.

In backhand strokes racket velocity was correlated with the velocities of playing-side arm abduction and playing-side shoulder girdle rotation. Coordination of these movements, which probably propel the more distal segments of the playing limb as part of a kinematic chain, appears to be based on the principle of proximal-to-distal sequencing.

As there is substantial between-player variation in

angular velocities, it seems that detailed evaluations of individual table tennis champions would be valuable.

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Key points

- The aim of this study was to calculate correlations between racket velocity and the angular velocities of individual joints and for variants of topspin forehand and backhand strokes in table tennis.
- A novel model was used to estimate range of motion (specially developed placement protocol for upper body markers and identification of a ball-racket contact using an acoustic sensor attached to the racket).
- In forehand strokes angular velocities of internal arm rotation and adduction in shoulder joint were correlated with racket velocity.
- Correlations between racket velocity and the angular velocities of playing- and non-playing-side hip extension and ankle flexion were found in topspin forehands.
- In topspin backhands abduction of the arm had the greatest impact on the racket speed.
- The results can be used directly to improve training of table tennis techniques, especially topspin strokes.

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