UNCONTROLLED MANIFOLD ANALYSIS OF JOINT ANGLE VARIABILITY DURING TABLE TENNIS FOREHAND

Yoichi Iino, Shinsuke Yoshioka and Senshi Fukashiro[1]

Graduate School of Arts & Sciences, The University of Tokyo, Tokyo, Japan[1]

The purpose of this study was to evaluate the variance structure of the trunk and racket arm joint angles in the table tennis topspin forehand in relation to the control of racket orientation using the uncontrolled manifold (UCM) approach. Seventeen (9 advanced and 8 intermediate) male collegiate table tennis players performed the strokes against backspin. The UCM analysis was conducted using 30 trial data per each participant. The degree of redundancy exploitation to stabilize the racket vertical and horizontal angles were not significantly different between the two performance levels, suggesting that the ability to exploit joint configuration redundancy may not contribute to achieving higher performance in sport hitting skill. The degree of redundancy exploitation is highest at ball impact and this result may reflect that the table tennis forehand is a fast interceptive task.

KEYWORDS: redundancy, interceptive task, racket sports.

INTRODUCTION: The topspin forehand is one of the most offensive shots in table tennis. A recent study (Malagoli Lanzoni et al, 2014) found it is more related to a winner than other strokes, suggesting that to master this shot is critical to winning a match. The movement variability has attracted growing attention of sports biomechanics community. The table tennis forehand has, however, yet to fully be investigated in this respect.

When considering the movement variability, it is important to note that execution of many motor tasks has more degrees of freedom (DOF) in control variables than in task variables (motor redundancy). The uncontrolled manifold (UCM) analysis (Scholz & Schoner, 1999, Latash et al., 2007) examines how control variables are coordinated with respect to task variables. In the UCM analysis, the variance of control variables is partitioned into that which affects task variables (Vorth) and that which does not (Vucm). If Vucm is larger than Votrh, the motor system is said to structure the variabilities of control variables or to exploit redundancy, in order to stabilize the task variable. This analysis has been successfully applied to a variety of motor tasks, including finger force production (Latash et al., 2001), throwing (Yang & Sholz, 2005), stone knapping (Rein et al., 2013), robotic teleoperation (Nisky et al, 2014) and golf swing (Morisson, et al, 2016) tasks.

In stone knapping (Rein et al., 2013) and robotic teleoperation (Nisky et al., 2014), experts showed a higher degree of redundancy exploitation to stabilize the positions of a hammer and the hand, respectively. In golf swing (Morisson et al., 2016), high-skilled golfers showed lower total variance per DOF than intermediate skilled golfers although the degree of redundancy exploitation to stabilize clubhead orientation was similar. Therefore, the UCM analysis may provide useful implications for skill assessment.

Previous studies (Bootsma & van Wieringen, 1990; Sheppard et al., 2007; van Soest et al., 2010) investigated how table tennis players control racket movements during the forehand that is a fast interceptive task, focusing on the utilization of visual information. A consensus has yet to be obtained as to whether racket movement is controlled under continuous visual guidance (Bootsma et al., 2010). Examining how the degree of exploitation of redundancy of the joint configuration changes during the forehand may shed some light on the mechanism of how racket movement is controlled.

The purpose of this study was to evaluate the variance structure of the joint angles using the UCM approach during the table tennis topspin forehand for advanced and intermediate players. Two hypothesis were tested: that advanced players show a higher degree of redundancy exploitation than intermediate players and that the degree of redundancy exploitation increases towards ball impact.

METHODS: Seventeen male collegiate table tennis players participated in the study. Nine players were Division I players (mean (s) age, height, body mass and playing experience were 20.4 (1.3) years, 1.72 (0.07) m, 65.3 (5.4) kg, and 11.3 (2.2) years) who had qualified for competing in some national championships in high school and/or college and categorized as "advanced". Eight were Division III players (20.9 (0.9) years, 1.73 (0.07) m, 62.5 (6.3) kg, and 7.8 (1.0) years) who had not qualified for national championships and categorized as "intermediate". All participant provided informed consent. The procedure was approved by the local ethics committee.

Participants were asked to hit topspin forehands against backspin aiming at a target on the table of opponent's court as fast and as accurately as possible. At least 30 trials were recorded for each participant. A motion capture system (MAC3D, Motion Analysis) was used to record 3D coordinates of the markers attached to the body surfaces of the trunk and upper limbs at 200 Hz. The positional coordinate data were smoothed using a zero-lag Butterworth digital low-pass filter.

The trunk and racket arm were modelled as 13 DOF link segments consisted of the pelvis, upper trunk, upper arm, forearm and hand + racket with 3, 3, 3, 2 and 2 DOF for pelvis rotation with respect to the ground, relative upper trunk rotation to the pelvis, the shoulder, the elbow/forearm and the wrist joints, respectively. Cardan angles were determined for each joint/segment rotation with a sequence of Y (mediolateral)-X (anteroposterior)-Z (superior-inferior) axes. According to the previous study (Sheppard et al., 2007), the task variables were the racket horizontal and vertical angles. The racket horizontal and vertical angles were defined as the angle between the horizontal projection of the normal vector of the racket face and the X axis of the global system, and the angle between the normal vector and the vertical axis, respectively. The rotation matrix of the racket with respect to the ground was determined as the product of the rotation matrices of the 13 DOF and the rotation matrix of the racket with respect to the hand. The racket angles can be derived from this matrix. The UCM analysis was performed using 30 trial data for each participant. In short, the deviation of the joint configuration from the mean configuration at each time instant was related to the deviation of the task variable from its mean by a Jacobian in the linearized form.

$$\mathrm{x} - \bar{\mathrm{x}} = J(\bar{\theta})(\theta - \bar{\theta}),$$

where x is a task variable, θ is the joint angle vector and $^{-}$ denotes the mean vector at each time instant. The deviation of the joint configuration from the mean was projected onto the null space of the Jacobian and the space orthogonal to the null space. The variance per the dimension of each subspace was determined and will be referred to as Vucm and Vorth, respectively. The ratio of Vucm to Vorth was determined to quantify to what degree the joint angles are coordinated to stabilize the task variables. Due to the non-normal distribution of the ratio of variances (Verrel et al., 2010), the logarithm of this ratio was determined:

$$\mathrm{Rv} = \ln\left({}^{\mathrm{Vucm}}/_{\mathrm{Vorth}}\right).$$

Two-way repeated measures ANOVA was used to compare the Vucm, Vorth, and Rv between the performance levels and among six different timings (-200ms, -150ms, -100ms, -50ms, 0ms and 50ms with respect to ball-racket impact, Figure 1). These specific timings were selected according to Sheppard et al. (2007). When the assumption of sphericity was not tenable, as indicated by Mauchly's test, the degrees of freedom were corrected using Hyunh–Feldt estimates of sphericity. When the main effect was significant, the post-hoc pairwise comparison was performed using Holm's method.

RESULTS: Two-way ANOVA revealed no significant interaction of performance level and timing on the Vorth, Vucm and Rv for the racket vertical and horizontal angles. No significant differences were observed between the advanced and intermediate players for the Vorth, Vucm and Rv. In contrast, the effects of timing on all dependent variables were significant (Figure 2). The Vorth for the racket vertical angle was significantly larger at 50ms after ball impact than the all the other timings (Figure 2A). The Vorth for the racket horizontal angle was similar among all timings except between 0ms and 50ms (Figure 2D). The Vucm at and after -50ms were generally larger than those before -50ms for both angles.

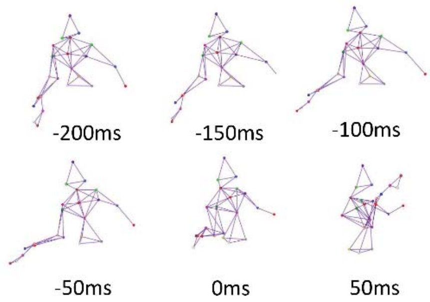

Figure 1: Movement sequence of the table tennis forehand for a player. Time 0ms indicates ball impact.

Rv is significantly larger than zero at all timings examined for both racket angles. The Rv for the racket vertical angle at -100ms, -50ms and 0ms were significantly larger than the Rv at most of the remaining timings (Figure 2C). In contrast, the Rv for the horizontal racket angle at 0ms was significantly larger than the Rv at the other timings (Figure 2F).

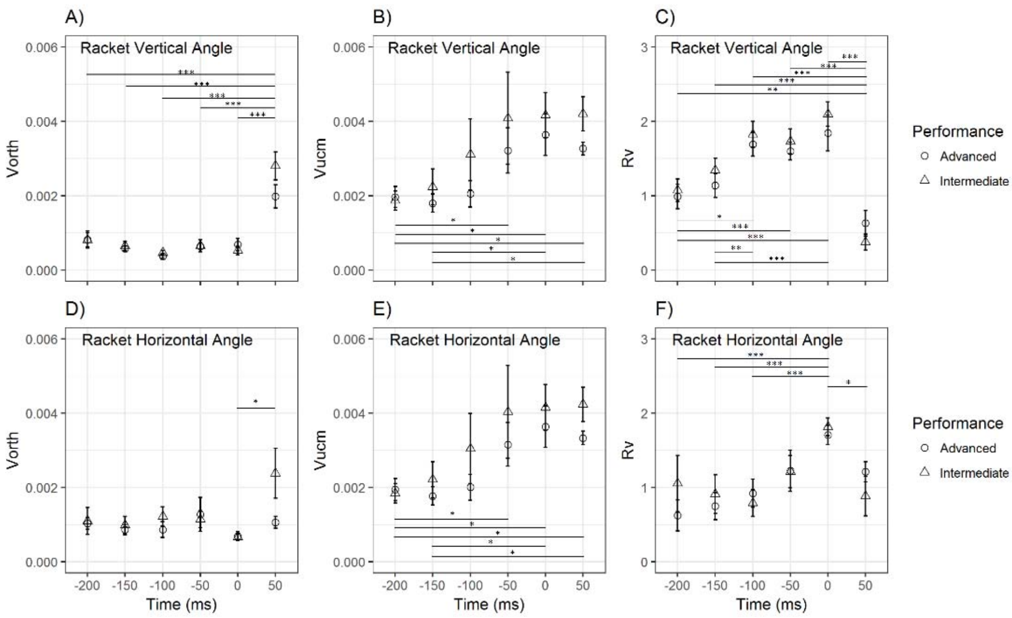

Figure 2: Vorth, Vucm and Rv (mean and se) for the racket vertical and horizontal angles for advanced and intermediate players. Horizontal lines indicate significant differences between timings (****P* < 0.001, ***P* < 0.01, **P* < 0.05). Time 0ms indicates ball impact.**

DISCUSSION:

The Rv for both racket angles showed no significant differences between advanced and intermediate players. Therefore, the first hypothesis was not supported. The result is consistent with Morrison et al. (2016) who reported that Rv was in general similar between high and intermediate skilled golfer. Rv indicates the degree the motor system exploit motor redundancy to stabilize a task variable. A previous study (Yang & Scholz, 2005) found that novices increased the degree of redundancy exploitation to stabilize hand orientation and movement direction just after five days of training in flying disk throwing. Combined with the results of the present study, it is suggested that the ability to exploit joint configuration redundancy is a rather fundamental human function and the greater ability may not contribute to achieving higher performance in sport hitting skills.

The Vorth and Vucm values were not significantly different between advanced and intermediate players. This is inconsistent with the result of Morrison et al. (2016), which reported lower variance in high skilled golfers than intermediate skilled golfers. The intermediate players in the present study had about 8 years of training experience in table tennis and apparently could swing a racket consistently. A study using populations with broader performance levels is required to examine the effect of performance level comprehensively.

The Rv showed the highest value at ball impact. The second hypothesis was supported. This is not so evident in the Rv with respect to clubhead orientation in the golf swing (Morrison et al., 2016). Table tennis stroke is an interceptive task and players are required to control racket movement to hit a moving ball appropriately. In light of the visuomotor delay of 100 – 200 ms, players cannot use visual information that is available after -100 ms to correct racket movement. This feature may be related to that the degree of redundancy exploitation is highest at impact in table tennis forehand.

CONCLUSION: This study quantified the degree of redundancy exploitation of the joint configuration in the table tennis forehand for advanced and intermediate players. The degree of redundancy exploitation to stabilize the racket vertical and horizontal angles were not significantly different between the two performance levels. Combined with previous studies, the results suggest that the ability to exploit motor redundancy is rather a fundamental human function and the greater ability may not contribute to achieving higher performance in sport hitting skill. The degree of redundancy exploitation is highest at ball impact. The result may reflect that the table tennis forehand is a fast interceptive task.

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