VARIABILITY AND THE CONTROL OF ROTATION DURING SPRINGBOARD DIVING

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This study explored the variability in angular velocity profiles across multiple somersault dives. Four international level divers performed 4-6 repeated dives of either 3½ somersaults with pike, or 4½ with tuck, from a 3 m springboard. An inertial measurement unit (IMU) was attached to the lower back to record angular velocity during all trials. Each diver produced highly consistent patterns of dive time duration and angular velocity, with standard deviations less than 1% of the mean. No consistent pattern of correlation between velocity and duration of the held tuck/pike position was apparent, and no other evidence of mid-dive feedback control was evident from the present methodology. This may be the result of performing dives with a high degree of difficulty, providing little time for movement adjustments during 'kick out' to affect water-entry.

KEY WORDS: springboard diving, variability, control, angular velocity.

INTRODUCTION: Dynamical systems theory suggests that a property of highly skilled movement is the capability to functionally control and introduce degrees of variability according to task requirements (Handford et al., 1997). However, whilst skilled performance often requires a high consistency of movement outcomes (low outcome variability), skilled performers will often exhibit a higher intra-limb variability to achieve these consistent outcomes (high coordination variability) (Wilson et al., 2008).

In the context of diving, O'Meara (2010) has previously showed high levels of consistency in terms of angular velocity patterns when elite divers performed forward tuck somersaults from the floor during dry land training. Specifically, coefficients of variation in average angular velocity ranged between 0.6-1.7%. Similar findings have also recently found in somersaults performed from a springboard (Walker et al., 2014). While it is difficult to directly compare measures of variability between different variables and in different performance contexts, coefficients of variation for other skilled performances have reported higher values; such as 5% for the last stride length of a long jump run-up (Galloway & Connor, 1999) or 7% for flight time of a standing somersault (Gittoes et al., 2011).

During a somersault dive, divers leave the springboard with a given amount of angular momentum and maintain a constant momentum until water entry (Sanders & Wilson, 1987). When performing dives that include multiple somersaults, divers maintain a tight tuck or pike position to reduce their moment of inertia, and therefore to assist rotational speed, before 'kicking-out' (i.e., increasing their mass moment of inertia and reducing the velocity of rotation). The diver then aims to achieve an extended and vertical position at the point of water entry with minimum splash. Therefore, being able to coordinate, control, and adjust movement presents a substantial challenge for divers. Understanding and identifying the process by which it can be achieved has important implications, least of all for coaching and performance optimisation.

This study firstly explored the degree of variability in angular velocity profiles across multiple somersault dive attempts. Secondly, it examined whether divers actively controlled the timing of the 'kick out' in accordance with variations in the velocity of rotation in an effort to assure accurate and reliable water entry.

METHODS: Four international level divers participated in this study. Each completed 4-6 forward somersault dives at their highest degree of difficulty from a three metre springboard. Two divers (D1, D2) performed the three and a half somersault dive in a pike position (3½P), and two (D3, D4) performed the four and a half somersault dive in a tuck position (4½T).

Angular velocity was measured using a waterproof inertial measurement unit (IMU) (IMeasureU, Ltd; Auckland, New Zealand) with embedded gyroscope, strapped to the lower back (at L4/L5) using a transparent film dressing (Opsite Flexigrid). Figure 1 illustrates a typical angular velocity profile from a 4½T dive. The initial negative velocity coincided with divers extending their body during board depression. Take-off time and departure from the springboard could not be accurately determined from the angular velocity trace, so dive time was counted from the point of maximum negative velocity through to water entry. Profiles for each diver displayed an initial velocity peak at the approximate point of completing half a rotation (Time 1.2 s, Figure 1). This point was used to define the start of a plateau region, where velocity remained relatively constant while divers held their full tuck/pike positions. An iterative procedure was then used to identify the plateau end point; when angular velocity dropped below the average velocity across the plateau. Angular displacement was calculated by numerical integration of the angular velocity across time. Within subject correlations were performed between selected kinematic variables to identify possible feedback mechanisms utilised by each diver.

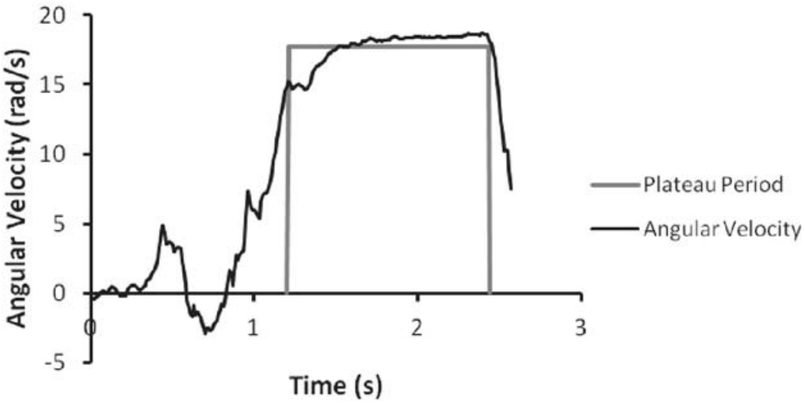

Figure 1: Angular velocity for one exemplar trial (4½T) illustrating calculation of the plateau region.

RESULTS AND DISCUSSION: Each diver produced a consistent pattern of performance, with high similarity between divers performing the same respective dive type (see Figure 2). Total dive time was consistent with standard deviations < 1.1% of total dive time (see Table 1). All participants displayed low variability between trials in angular velocity (0.5 - 1.0%), and in plateau duration time (1.5 - 2.3%). All participants except D4 produced less variability between trials in their angular velocity measures (□1%) than they did for variability in the plateau duration (1.5 - 2.3%).

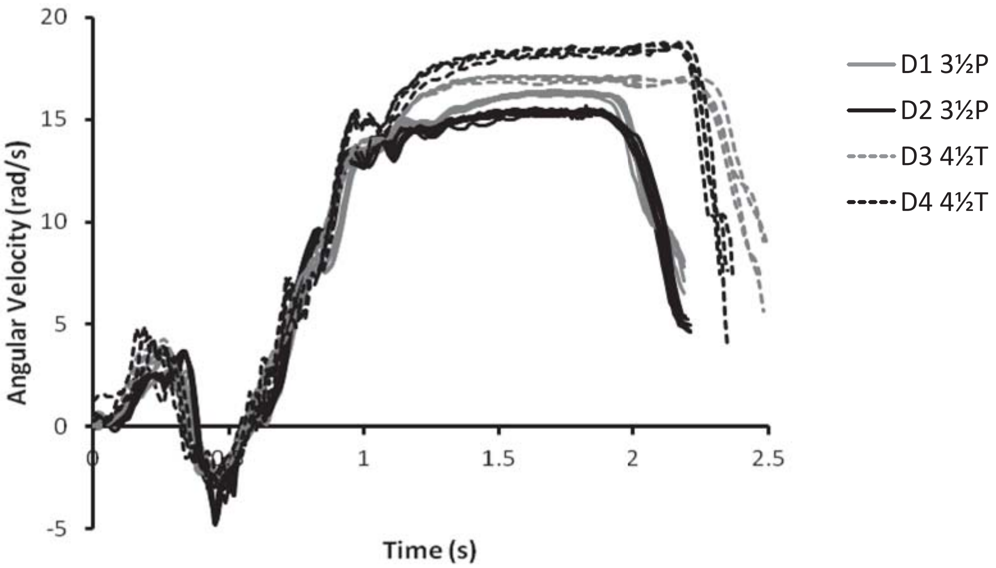

Figure 2: Angular velocity profiles for all trials of each participant (D1 – D4).

Table 1: Mean and coefficient of variation for all kinematic measures and selected correlations. Data represent the mean of all trials completed by each diver, D1-D4.

	D1 3½P (n=5)	D2 3½P (n=6)	D3 4½T (n=4)	D4 4½T (n=4)
Duration of dive (s)	1.74 ± 0.6%	1.75 ± 0.6%	2.03 ± 0.4%	1.90 ± 1.1%
Duration of plateau (s)	0.97 ± 1.8%	0.94 ± 1.5%	1.26 ± 2.3%	1.25 ± 1.5%
Velocity of plateau (° s^{-1})	888 ± 0.5%	844 ± 0.7%	944 ± 0.6%	1009 ± 1.0%
Rotation before plateau (°)	156 ± 2.5%	154 ± 3.3%	186 ± 1.0%	160 ± 3.1%
Rotation during plateau (°)	855 ± 0.9%	796 ± 1.3%	1202 ± 2.8%	1267 ± 1.6%
Rotation after plateau (°)	148 ± 7.6%	191 ± 3.7%	160 ± 13.1%	103 ± 10.8%
Total rotation (°)	1160 ± 0.7%	1141 ± 0.7%	1548 ± 1.0%	1530 ± 1.2%
Correlation between the amount of rotation and the duration of plateau	+0.83*	+0.87**	+0.99**	+0.82*
Correlation between the amount of rotation and the velocity of plateau	$+0.63^{ns}$	-0.14^{ns}	$+0.70^{ns}$	$+0.45^{ns}$
Correlation between the velocity of rotation and the duration of plateau	$+0.63^{ns}$	-0.53^{ns}	$+0.58^{ns}$	-0.14^{ns}
Correlation between the rotation before opening out and rotation after opening out	-0.72^{ns}	-0.87**	-0.92*	-0.57^{ns}

* Correlation is significant (p□0.05). ** Correlation is significant (p□0.01). ns indicates correlation is not significant (p>0.05).

Between 70 and 83% of the total rotation for each dive was produced during the plateau region where divers held a fixed tuck/pike position. Consistency during this portion of the dive is therefore very important if divers are to achieve the required amount of rotation to enter the water in a reasonably upright position. This high degree of consistency between dives is a necessary requirement to land a dive safely and with minimal splash. During the plateau, all divers rotated between 8-10° every 0.01s. Consequently, changing the plateau velocity or duration by only 1% would change the amount of rotation between 9-13°, depending on the divers' velocity and duration.

There was relatively low variability in total rotation (• = 0.9%) compared with the amount of variability before the plateau (• = 2.5%), during the plateau (• = 1.7%) or after the plateau (• = 8.8%). The total rotation represents low outcome variability, as would be expected for experienced performers. The individual component rotations, while not exactly the same concept as the coordination variability between segments described by Wilson et al. (2008), is consistent with this theory as the skilled performers are able to link these more variable component rotations together to produce a consistent total rotation before water entry.

A strong correlation was evident for all divers between plateau duration and the amount of rotation during this period (+0.88 ± 0.08). Correlations between the amount of rotation and angular velocity were comparatively weaker (+0.41 ± 0.38), suggesting that tuck duration had a greater association with the amount of rotation achieved. If divers were modulating the duration of their plateau region to achieve a consistent amount of rotation we would have expected a negative correlation between rotation velocity and plateau duration. There is no evidence that divers did this; however, with only one diver showing a moderate negative correlation between velocity and duration of plateau. Indeed, two participants demonstrated a positive correlation, where the faster rotations also had a longer duration of the plateau.

Negative correlations were found for all divers (-0.77 ± 0.16) between the amount of rotation occurring before the end of the plateau and the amount of rotation after the plateau. Part of this effect would occur largely because, if divers held the tuck longer, producing more rotation during the plateau, then there would be less time available for rotations to occur after the plateau.

Perhaps athletes control the rate they open out after the plateau in order to control water entry. While Figure 2 demonstrates there were differences between divers in the rate of velocity decline after the plateau, there was no apparent pattern to the variation between dives. For example, participant D3 performed two dives where the velocity decline was more rapid than the other two; however, those were not dives where more rotation had occurred before the end of the plateau. Further consideration will need to be given to methods for quantifying movement control during the opening out portion of a dive. Such methods will likely need to consider changes in shape of the velocity profile after the plateau, not simply the average slope of the curve.

The 3½P and 4½T dives investigated in this study were of the highest degree of difficulty able to be performed by these particular divers. Perhaps the divers were merely trying as hard as they could to complete the required number of revolutions, and had no spare capacity to controllably adjust their position for entry. Further research will use more trials and consider dives with lower numbers of rotations to see how body position is controlled prior to entry.

CONCLUSION: A high degree of consistency in angular velocity appears necessary when performing multiple somersaults as part of a successful dive. Divers may have regulated the duration and velocity of their somersaults to within 1% of variability because to do otherwise would have resulted in a ten degree change in total rotation for the dive. There is no explicit evidence to suggest that divers were able to intentionally manipulate the timing of 'opening-out' from a tuck/pike position in response to variations in velocity of rotation. Thus, we remain reserved in understanding and recommending whether and how diving movements can be controlled prior to water entry. To progress from this position, it is proposed that examining dives with a lower number of required rotations, and consequently with a lower degree of difficulty, may provide better insight as to whether highly skilled divers can controllably modify their angular velocity in mid-flight to affect the angle of water entry.

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