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Functional variability in the flight phase of one metre springboard forward dives

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ABSTRACT

In springboard diving, low variability in takeoff conditions and in the somersault orientation angle at water entry is to be expected since consistency and accuracy are necessary for a good dive. A diver's adjustment of body configuration during flight may be a deliberate compensation for variations in takeoff conditions, leading to increased joint angle variability and decreased entry angle variability. The aim of this research was to investigate the extent to which a diver pre-plans the aerial phase and then makes adjustments in flight to control the entry angle in one metre springboard forward dives. Performances of 15 forward pike dives and 15 forward 2½ somersault pike dives, performed by an international diver were video recorded at 250 Hz. Joint centres during flight were digitized and their spatial coordinates were subsequently reconstructed using the Direct Linear Transformation in order to determine orientation and configuration angles. A computer simulation model was used to investigate the effects of variability in takeoff conditions and configuration variability in flight on the variability of the orientation angle at water entry. The amount of variation in the somersault orientation angle at entry as determined using simulations based on the variability in the takeoff conditions was four times greater than the variation in the recorded performances. It was concluded that the diver used open loop control for the first half of the flight phase and subsequently used feedforward and feedback control to make timing adjustments of hip and arm angles to reduce the variability of his entry orientation angle.

INTRODUCTION

Many competitive sports incorporate an aerial phase within which acrobatic movements are performed as in gymnastics, trampolining and springboard diving. For competitive springboard diving the main mechanical objectives are: generating sufficient angular momentum, obtaining maximum dive height and therefore flight time, travelling safely away from the board, and having the correct orientation angle on entry into the water (Miller & Munro, 1985). The latter is often considered one of the primary performance outcomes of the dive, since it is the last part of the movement the judges see, with incorrect orientation at entry accompanied by greater splash of the water. Success in competitive diving requires consistency in achieving appropriate somersault orientation at water entry. This paper seeks to understand how such consistency is achieved.

A springboard dive can be divided into (a) the hurdle phase, (b) the contact phase, and (c) the aerial phase (Figure 1). The hurdle and contact phases are used to generate the linear and angular momentum for the subsequent aerial phase and to ensure the diver travels safely away from the board. The aerial phase is used to complete the required number of rotations and achieve the correct orientation at entry.

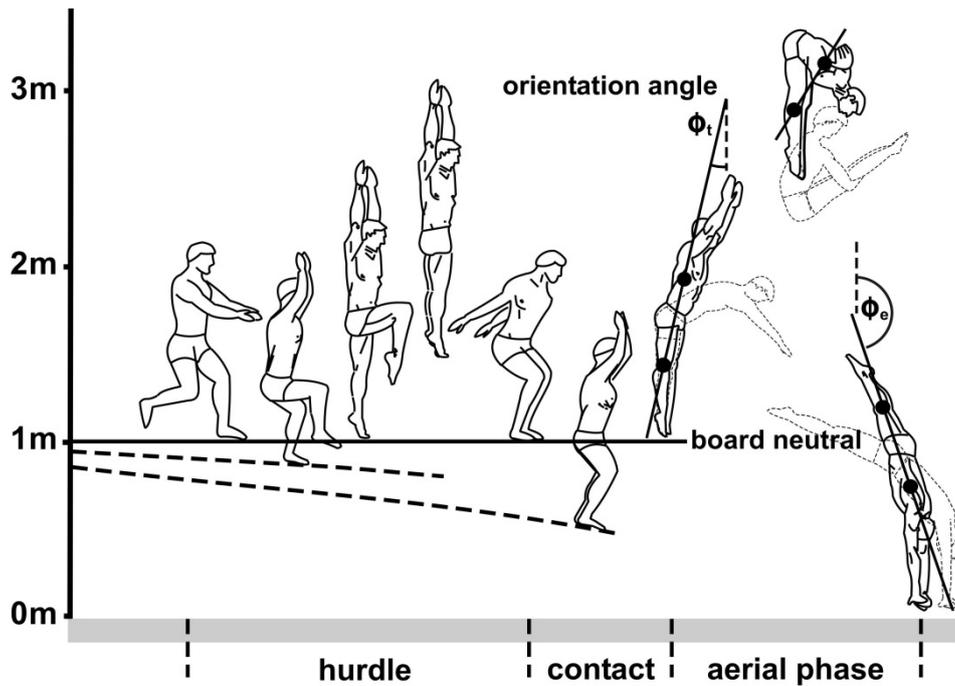


Figure 1. One metre springboard forward pike dive (solid line) and forward 2½ somersault pike (dotted line) dive. Phases comprise: hurdle (contact and flight), contact, flight. ϕ_t = orientation angle at takeoff at board neutral position, ϕ_e = entry orientation angle.

When an expert diver aims to perform a given dive in exactly the same manner on each attempt (open loop control), it is inevitable that there will be some variation from trial to trial (Newell & Corcos, 1993; Bartlett, Wheat, & Robins, 2007; Preatoni et al., 2013). If the performance variability in one stage is incorporated into the planning of the next stage (feedforward control) the propagated variation may be reduced. For example if the diver senses that the horizontal velocity in the hurdle flight is greater than usual he may modify the plan for the takeoff muscle activations in order to be nearer the ideal horizontal velocity at the moment of takeoff. In rapid movements of short duration carried out with feedforward control, such as the contact phase in tumbling of around 0.1 s (King & Yeadon, 2004), kinematic movement variability may arise due to errors in the localisation (estimation of initial conditions) and planning stages of the movement, and also due to noise within in the execution stage of the movement (van Beers, Haggard & Wolpert, 2004). If the movement is longer in duration, such as the contact and aerial phases of one-metre springboard diving with times of around 0.5 s and 1.3 s (Miller, Zecevice, & Taylor, 2002), there is sufficient time for the diver to make corrections for such errors. That is, the diver may use feedback control (Jagacinski & Flach, 2003) to adjust body configuration in flight to ensure an accurate entry to the water. Such feedback corrections, using changes in arm and hip angles, would add to the kinematic movement variability (Hiley, Zuevsky, & Yeadon, 2013).

Traditionally movement variability has been viewed as noise that needs to be minimised or eliminated (Newell & Corcos, 1993). More recently, researchers have been interested in the potentially functional role that variability may play in human movement (Preatoni et al., 2013; Bartlett et al., 2007; Hiley & Yeadon, 2016). For example, an increase in movement variability associated with a diver making feedback corrections in flight would fall under the definition of functional variability, since the adjustments could have the function of controlling the somersault rotation

in order to ensure appropriate orientation on entry into the water. In other words the adjustments produce increased movement variability in flight leading to a reduction in outcome variability on entry to the water.

Feedback control has been demonstrated in a number of acrobatic activities such as handstand balance (Yeadon & Trewartha, 2003), swinging on bars (Hiley & Yeadon, 2016) and twisting somersaults (Yeadon & Mikulcik, 1996; Yeadon & Hiley, 2014). In each case the control strategy was found to use a combination of open loop control or feedforward control together with feedback (closed loop) control to achieve the task goals. The feedback control was based on detecting an error in the desired state and providing a correction, after an inherent time delay (Latash, 1998; Jagacinski & Flach, 2003). For example, Hiley and Yeadon (2016) demonstrated that gymnasts made adjustments (feedback control) to their pre-planned movements to regulate the pace of consecutive backward longswings on the horizontal bar. In springboard diving it might be expected that the diver pre-plans the aerial phase (either open loop control or feedforward control) and then makes adjustments during flight (feedback control) to correct for errors generated during the contact phase. The aim of the present study is to determine to what extent divers pre-plan the aerial phase and make adjustments in flight in order to minimise the variability in somersault orientation on entry into the water. Specific questions to be answered comprise: (a) are in-flight adjustments made using arm or hip angle changes in response to variation in rotation potential at takeoff? (b) is a single adjustment made or are sequential adjustments employed? (c) are there differences in the adjustments made in pike dives and in 2½ somersault pike dives?

METHODS

In order to answer the above questions repeated performances of the same dive by the same diver were conducted in order to obtain variability measures of the same dive / diver activity. The performances were video-recorded and time histories of somersault orientation and joint angles were calculated from projections of digitised body landmarks on a vertical plane. A simulation study was used to establish whether in flight corrections must have been made to obtain low variability in the somersault entry angle. Subsequently linear regression was used to identify whether adjustments of arm angle or hip angle were related to variation in rotation potential and somersault orientation angle.

DATA ACQUISITION AND PROCESSING

A male international springboard diver (age 21 years, mass 70 kg, height 1.8 m) performed 15 forward pike dives (101B) in the morning and 15 forward 2½ somersault pike dives (105B) in the afternoon from the one metre springboard. In the dive code the first numeral indicates the dive group (1 = forward), the second indicates the takeoff position (0 = from the feet), the third gives the number of half somersaults (5 = 2½ somersaults), and the final letter defines the body configuration in flight (B = pike). Before data collection, the purpose and details of the study were explained to the diver and all procedures were approved by the Loughborough University ethics committee. A Fastec TS3 high speed camera placed to the side of the springboard was used to record all performances at a frequency of 250 Hz. A calibration pole with seven markers spaced at one metre intervals was placed in three positions on the nearside pool deck and in three positions on the far side pool deck, spanning the hurdle and flight phase volume. A Direct Linear Transformation

(DLT) procedure was used to reconstruct digitised points as projections onto a vertical plane through the right hip when standing symmetrically on the board. The following points were digitised manually: wrist, elbow, shoulder, hip, knee, ankle, ball of foot, and toes on each side of the body, the centre of the head and the tip of the springboard. Hip angle was calculated as the angle between the line joining mid-hip joint centres and mid-knees and the line joining mid-hip and mid-shoulder joint centres, with 180° corresponding to a straight body position. Knee angle was calculated as the angle between the line joining mid-knee joint centres and mid-hip joint centres and the line joining mid-knees and mid-ankles, with 180° corresponding to straight legs. It was expected that the legs would be straight throughout the flight phase of each dive. The angle between each arm and the centre line of the trunk allowed out of plane movement and was calculated from the projected inclination and projected length of the arm on the vertical calibration plane. Left and right arm angles were averaged and 180° corresponded to arms overhead. Joint angle time histories were calculated as in Yeadon (1990a).

The body segmental inertia parameters were calculated from anthropometric measurements taken from the diver using a mathematical inertia model (Yeadon, 1990b). The inertia parameters were used to calculate the mass centre location with horizontal and vertical velocities at touchdown and takeoff calculated using linear and quadratic fits to the displacement-time data in the flight phases. Whole body orientation was calculated as the angle between the vertical and a line from the midpoint of the knee centres to a point on the spine 60% of the distance from mid-hip centre to mid-shoulder centre (Figure 1). The use of such a body reference frame is less sensitive to changes in hip angle than a body frame embedded in a single segment (Yeadon, 1990c).

SIMULATION MODEL

An 11-segment simulation model of aerial movement (Yeadon, Atha, & Hales, 1990) was used to investigate the effect of variability of (a) initial conditions at takeoff (b) configurational changes during flight on simulated entry angle variability. Angular momentum about the mass centre was determined for each dive iteratively, starting from an initial estimate (Yeadon, 1990c), so as to give the same entry angles as obtained from the video analysis. The rotation potential of each dive was calculated as the product of angular momentum ($\text{kg}\cdot\text{m}^2\cdot\text{s}^{-1}$) and flight time (s) divided by 2π times the moment of inertia of the body in the anatomical position, giving the equivalent number of straight somersaults (Hiley & Yeadon, 2008). Segmental inertia parameters were obtained as in (Yeadon, 1990b). The model input comprised the initial somersault orientation angle, rotation potential, joint angle time histories at shoulder, hip and knee together with the flight time. The equation of motion corresponding to constant angular momentum about the mass centre was solved for the somersault rate and the somersault orientation angle was obtained by integration using Merson's form of the Runge-Kutta method (Lambert, 1973). The model output comprised the orientation angle time histories during the simulation of the 15 forward pike and 15 forward $2\frac{1}{2}$ somersault pike dives and these were compared with the orientation angle time histories from the recorded performances.

Two analyses were carried out for each of the two types of dive to investigate whether adjustments were made in the flight phase to control the somersault orientation angle at entry. In the first analysis, the variability in the entry angle arising from the variability of takeoff conditions was determined. For each trial, flight time

and angular momentum of the 15 dives were used as input into the model while retaining the joint angle time histories of that trial, thereby producing 15 simulations of that trial and 225 simulations in total. The variability of the mean entry angle obtained from each trial group of simulations indicates the variability arising from the vertical velocity and angular momentum at takeoff. This reveals how the entry angle varies as a function of variation in the takeoff conditions without changing the body configuration during the flight phase.

In the second analysis, the variability in entry angle arising from the joint angle changes during the flight phase was investigated. For each trial the time histories of the joint angles of all 15 dives were used as input into the model while retaining the flight time and angular momentum of that trial, again involving 225 simulations in total. The variability of the mean entry angle obtained from each trial group of simulations gives the variability arising from the body configuration during the flight phase. This indicates how the entry angle varies as a function of the body configuration during the flight phase without changing the takeoff conditions. A combined analysis was also carried out by calculating the sum of the net changes from the recorded entry in analysis 1 and analysis 2 for each of the 15 trials in order to estimate the entry angle variability arising from variation in the initial conditions and in the configurational changes.

REGRESSION ANALYSIS

Linear regression analysis was used to investigate whether adjustments were made in flight to reduce the variability in the orientation angle at entry. If the rotation potential at takeoff was less than planned then this might be compensated for by using a tighter pike (smaller hip angle) or by delaying the extension from the pike. Subsequent adjustment might be made if the orientation angle at the time of extension was less than or greater than planned. Such adjustments could be made by raising the arms to slow the somersault or using a smaller hip angle to increase the somersault rate.

Forwards stepwise linear multiple regression analyses were carried out using SPSS v.23 to investigate the relationships between the rotation potential and mean hip angle (for each dive), minimum hip angle, mean arm angle and minimum arm angle for the two types of dive (101B and 105B). An F-to-enter value corresponding to $p = 0.05$ was used for the inclusion of a variable in a regression equation. Regression models were rejected if coefficient 95% confidence intervals included zero or if correlations, tolerance statistics or variance inflation factors showed any evidence of multicollinearity (Bowerman and O'Connell, 1990; Myers, 1990; Menard, 1995; Field, 2013). Shapiro-Wilk tests (Field, 2013) were carried out and indicated no evidence against the assumption of normality of residuals.

Additional regressions investigated the relationships between joint angles at times of maximum variation and rotation potential in order to see whether adjustments were made on the basis of rotation potential. Regressions between a joint angle at a time of maximum variation and the orientation angle at an earlier time of maximum variation of the other joint angle investigated whether subsequent corrections were made based upon how well the earlier adjustment was progressing. Feedback control adjustments are necessarily based upon an assessment of an earlier state of the system since there is a time delay associated with the assessment.

RESULTS

The standard deviations of orientation and joint angles at takeoff and entry, centre of mass velocities, flight times and angular momenta were all small showing that the diver was consistent from trial to trial (Tables 1, 2). The mean orientation angles at takeoff and entry in 101B were $13^\circ \pm 1.3^\circ$ and $165^\circ \pm 2.3^\circ$, indicating that the body orientation was consistent at the start and end of the flight phase in the pike dives (Table 1). The corresponding values in the $2\frac{1}{2}$ somersault pike dives were $40^\circ \pm 1.9^\circ$ and $131^\circ \pm 4.7^\circ$, again showing consistency in 105B (Table 2). The mean rotation potential was 0.31 straight somersaults for 101B compared to 1.15 straight somersaults for 105B (Tables 1, 2).

Table 1. Angles and vertical velocity at takeoff and entry, flight time, angular momentum, horizontal velocity and rotation potential during the flight phase for 15 forward pike dives

Variable	Takeoff	Entry
Hip ($^\circ$)	168 ± 3.3	180 ± 3.6
Knee ($^\circ$)	179 ± 0.8	180 ± 0.6
Arm ($^\circ$)	157 ± 7.5	149 ± 4.9
Orientation ($^\circ$)	13 ± 1.3	165 ± 2.3
Vertical Velocity (ms^{-1})	5.8 ± 0.09	7.4 ± 0.06
Flight time (s)	1.349 ± 0.014	
Angular Momentum ($\text{kg.m}^2.\text{s}^{-1}$)	17 ± 1.0	
Horizontal velocity (ms^{-1})	0.86 ± 0.06	
Rotation potential (straight somersaults)	0.31 ± 0.02	

Table 2. Angles and vertical velocity at takeoff and entry, flight time, angular momentum and horizontal velocity during the flight phase for 15 forward $2\frac{1}{2}$ somersault pike dives

Variable	Takeoff	Entry
Hip ($^\circ$)	109 ± 5.0	142 ± 13
Knee ($^\circ$)	179 ± 1.8	177 ± 1.2
Arm ($^\circ$)	101 ± 7.3	138 ± 6.1
Orientation ($^\circ$)	40 ± 1.9	131 ± 4.7
Vertical Velocity (ms^{-1})	5.2 ± 0.08	6.8 ± 0.08
Flight time (s)	1.221 ± 0.015	
Angular momentum ($\text{kg.m}^2.\text{s}^{-1}$)	70 ± 1.7	
Horizontal velocity (ms^{-1})	1.1 ± 0.07	
Rotation potential (straight somersault)	1.15 ± 0.03	

The average root mean square (RMS) difference in orientation angle time history between simulation and performance was 3.1°, indicating that simulation closely matched performance. Simulation analysis 1 resulted in more variation in the orientation angle at water entry, arising from the variation in the takeoff values of vertical velocity and angular momentum, compared to the entry angle variation in the recorded dives. For the 15 forward pike dives the simulated variation in entry angle was 8.0° (Table 3) compared to the recorded variation of 2.3° (Table 1). For the 15 forward 2½ somersault pike dives the simulated variation in entry angle was 21.0° (Table 4) compared to the recorded variation of 4.7° (Table 2).

Simulation analysis 2 produced similar variations in entry angles, arising from the variation in joint angle time histories. For the 15 forward pike dives the simulated variation in entry angle was 9.3° (Table 3) and for the 15 forward 2½ somersault pike dives the simulated variation in entry angle was 19.7° (Table 4). The combined effect of analysis 1 and analysis 2 gave a simulated variation in entry angle of 2.4° for the 15 forward pike dives (Table 3) and 5.2° for the 15 forward 2½ somersault pike dives (Table 4).

Table 3. Entry angles (°) of forward pike dives and mean values of 15 simulations when initial conditions are varied (Analysis 1) and when body configuration in flight is varied (Analysis 2)

Trial	Recorded Entry	Analysis 1	Analysis 2	Combined Change*
		Mean Entry	Mean Entry	
Sim01	161.0	174.4	152.6	4.9
Sim02	165.3	163.4	167.3	0.1
Sim03	163.6	174.5	155.0	2.3
Sim04	167.6	162.2	170.7	-2.2
Sim05	166.6	148.8	184.9	0.5
Sim06	170.4	157.7	178.0	-5.1
Sim07	166.6	176.1	156.4	-0.7
Sim08	163.7	153.1	176.3	2.0
Sim09	164.8	171.0	159.3	0.8
Sim10	162.6	171.4	157.0	3.2
Sim11	164.3	167.3	162.3	1.0
Sim12	163.9	161.6	167.4	1.2
Sim13	163.6	169.9	159.3	2.0
Sim14	164.6	165.1	164.9	0.8
Sim15	167.0	164.1	168.2	-1.7
Mean	165.0	165.4	165.3	0.6
SD	2.3	8.0	9.3	2.4

* Note: the combined effect of Analysis 1 and Analysis 2 is the sum of the net changes from the recorded entry in each row

Table 4. Entry angles (°) of 2½ somersaults dives and mean values of 15 simulations when initial conditions are varied (Analysis 1) and when body configuration in flight is varied (Analysis 2)

Trial	Recorded Entry	Analysis 1	Analysis 2	Combined Change*
		Mean Entry	Mean Entry	
Sim01	131.4	160.9	98.6	-3.3
Sim02	135.7	126.5	135.4	-9.5
Sim03	132.6	113.6	143.9	-7.8
Sim04	136.3	124.7	138.1	-9.8
Sim05	138.1	163.3	102.0	-10.9
Sim06	127.9	112.4	141.9	-1.5
Sim07	127.4	93.4	164.7	3.3
Sim08	129.4	103.9	151.7	-3.2
Sim09	133.9	128.7	131.6	-7.5
Sim10	123.4	116.2	136.1	5.5
Sim11	123.9	112.2	137.1	1.5
Sim12	132.7	119.6	139.6	-6.2
Sim13	132.5	159.3	100.3	-5.4
Sim14	129.6	121.5	134.5	-3.3
Sim15	123.1	141.2	108.6	3.6
Mean	130.5	126.5	130.9	-3.6
SD	4.7	21.0	19.7	5.2

* Note: the combined effect of Analysis 1 and Analysis 2 is the sum of the net changes from the recorded entry in each row

The configuration changes during flight were adjusted as a function of the takeoff conditions. When rotation potential was regressed against mean hip angle and mean arm angle, only the mean hip angle was included as a predictor in each of the two cases, with the mean hip angle increasing with the rotation potential (Table 5). For the pike dives the mean hip angle explained 91% of the variance in rotation potential ($p < .01$) and 89% ($p < .01$) for the 2½ pike dives (Table 5). When rotation potential was regressed against minimum hip angle and minimum arm angle, no predictors were included.

Table 5. Stepwise multiple regression analysis of rotation potential against mean hip angle and mean arm angle during the flight phase of 15 forward pike dives (101B) and 15 forward 2½ somersault pike dives (105B)

Dive	R ²	coefficients		p
		unstandardised	standardised	
101B	0.908	constant	0.056	0.025
		mean hip angle	0.00230	0.953
105B	0.893	constant	0.572	< 0.001
		mean hip angle	0.00888	0.945

predictors: (constant), mean hip angle (°)
dependent variable: rotation potential (straight somersaults)

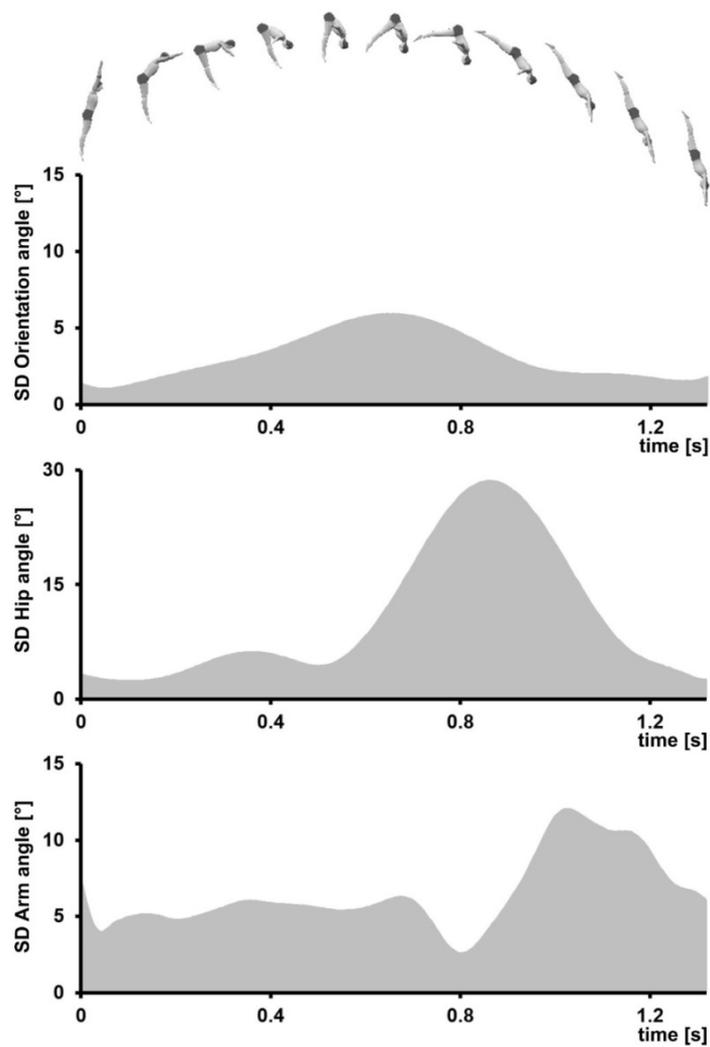


Figure 2. Time histories of the standard deviations in: (a) orientation angle, (b) hip angle, (c) arm angle for the 15 forward pike dives.

During the first half of flight the configurational changes were very similar with trial to trial differences in later flight. For both dives the variation in the orientation angle increased to a maximum in mid-flight and then decreased to a low value at entry (Figures 2, 3). The variation in the hip angle was small in the first half of flight rising to a maximum after around 0.8 s before starting to fall again (Figures 2, 3). For 101B the hip variation became small again at the end of the dive but for 105B it became large again (Figures 2, 3). The variation in the arm angle was small for the majority of the flight, rising to a maximum after around 1.0 s for 101B and 1.1 s for 105B before falling to a low value at entry (Figures 2, 3).

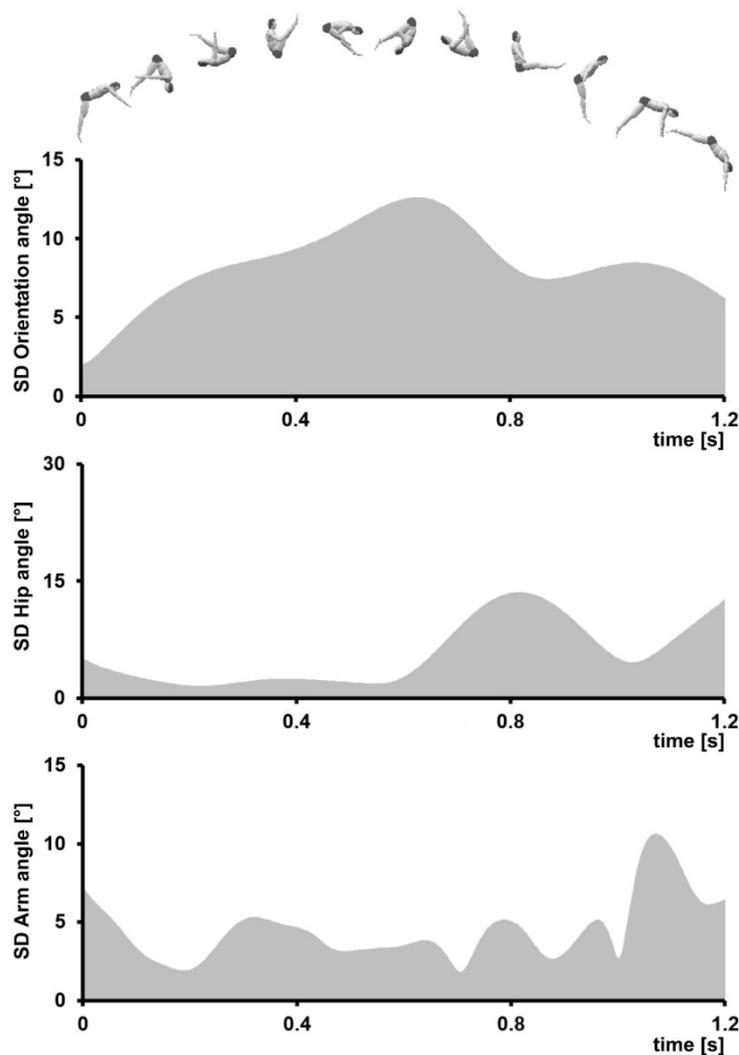


Figure 3. Time histories of the standard deviations in: (a) orientation angle, (b) hip angle, (c) arm angle for the 15 forward 2½ somersault pike dives.

Somersault rotation in flight was controlled by hip angle adjustment and also arm angle adjustment in the case of the 2½ somersault dive. When the hip angle at the time of maximum hip variation was regressed against rotation potential, positive relationships were obtained for both dives, with greater hip angle for greater rotation

potential (Table 6). When the arm angle at the time of maximum arm variation was regressed against the orientation angle at the earlier time of maximum hip variation, there was no relationship for 101B but a positive relationship for 105B, with greater arm angle associated with greater orientation angle (Table 7). When the final hip angle of 105B was regressed against the orientation angle at the earlier time of maximum arm angle variation, a positive relationship was found, with greater final hip angle associated with greater orientation angle (Table 7).

Table 6. Linear regression analysis of hip angle at maximum hip variation against rotation potential of 15 forward pike dives and 15 forward 2½ somersault pike dives

Dive	R ²	coefficients		p
		unstandardised	standardised	
101B	0.807	constant	-330.7	< 0.001
		rotation potential	1430.2	0.898 < 0.001
105B	0.766	constant	-392.9	< 0.001
		rotation potential	403.5	0.875 < 0.001

predictors: (constant), rotation potential (straight somersaults)
dependent variable: hip angle (°) at max hip angle variation (101B at 0.864 s, 105B at 0.820 s)

Table 7. Linear regression analysis of (a) arm angle at maximum arm variation against orientation angle at maximum hip variation and (b) hip angle at entry against orientation angle at maximum arm variation of 15 forward 2½ somersault pike dives

Analysis	R ²	coefficients		p
		unstandardised	standardised	
(a)	0.371	constant	-454.9	0.033
		orientation angle	0.812	0.609 0.016
(b)	0.453	constant	-672.6	0.017
		orientation angle	1.021	0.673 0.006

(a) predictors: (constant), orientation angle (°) at max hip variation (0.82 s)
dependent variable: arm angle (°) at max arm variation (1.072 s)
(b) predictors: (constant), orientation angle (°) at max arm variation (1.072 s)
dependent variable: hip angle (°) at entry (1.2 s)

DISCUSSION

The aim of the present study was to investigate the extent to which configuration changes during the flight phase control the entry angle in one metre springboard forward dives. A single subject design was used to control for variation in anthropometry, strength and technique. As the aim was to understand how variability in a diver's movements is related to dive outcome, a single subject design should not be viewed as a shortcoming since it is necessary for such an investigation into movement variability. It could be argued that the ideal entry angle is a function of the angular velocity at entry and this will contribute to the entry angle variability if the diver incorporates this into his corrections. It can be shown that the corresponding increase in variability is only a fraction of a degree which would not affect the current analysis.

The simulation analyses showed that adjustments must have been made in flight in order to achieve a consistent entry angle despite variations in takeoff conditions. The first simulation analysis showed that variability in the vertical velocity and angular momentum at takeoff, together with a fixed technique during flight, produce three or four times the variability in entry angle than in the recorded performances (Tables 1 - 4). This implies that adjustments must have been made during flight. In other words each flight phase in the recorded performances appears to have been tailored to the corresponding takeoff parameters. The second simulation analysis showed that the variation of body configuration over 15 trials produced similar variability in entry angle to the first analysis (Tables 3, 4). Again this indicates that the combination of takeoff parameters and body configuration in flight are linked. The variability in the entry angle from the second analysis produced a change in orientation on entry that was in the opposite direction to that of the first analysis so that the combined effects produced variability in entry angle similar to the recorded trials (Tables 1 - 4).

Variation in rotation potential at takeoff was adjusted for in flight by modifying the hip angle time history. The mean hip angle during flight of each trial was able to explain around 90% of the variation in rotation potential, showing that the hip angle was the primary means of adjustment during the flight phase (Table 5). Since the minimum hip angle during flight was not significantly correlated with the rotation potential, it must have been the timing of the hip angle changes that was adjusted. The variation in the hip angle was small in the first half of flight rising to a maximum after around 0.8 s before starting to fall again (Figures 2, 3). This indicates that open loop (fixed technique) was employed for the first part of flight with feedforward or feedback control (adjustments) of the hip angle being used subsequently. The variation in the arm angle was small for the first three quarters of flight rising to a maximum late in flight before falling to a low value at entry (Figures 2, 3), suggesting that the arms made a correction after the first hip angle adjustment. For the 2½ somersault dives the hip angle variability became large at entry (Figure 3), suggesting that a final hip angle adjustment was made. It is likely that the diver plans the aerial phase in advance (Miall & Wolpert, 1996; Wolpert, 1997; van Beers et al., 2004), including adopting the correct piked configuration, based on the expected linear and angular momenta. During the period from takeoff until before the point of maximum hip angle variation the diver evaluates the planned movement in relation to the actual values of the initial conditions or the current state (Miall & Wolpert, 1996; Wolpert, 1997). This evaluation most likely uses information relating

to the orientation angle or angular velocity. If there is a discrepancy between the predicted movement and the current state, the pre-planned movements (open loop control) are then adapted (feedforward control or feedback control) so that the diver either stays in the piked shape for longer or opens out earlier, leading to the increased recorded variation in hip angle.

The primary means of controlling the somersault rotation in flight was a single hip angle adjustment, followed by subsequent arm and hip adjustments for the more complex $2\frac{1}{2}$ somersault dive. The hip angle at the time of maximum hip angle variation was positively correlated with rotation potential for both dives (Table 6), with greater hip angle for greater rotation potential, indicating that the hip angle variation constituted an adjustment based on the variation in rotation potential. When the rotation potential was greater so was the hip angle at this time thereby increasing the moment of inertia to slow the somersault. Alternatively this may be viewed as an earlier opening of the hip angle when the rotation potential was greater. Modifying the time of opening from the pike position from the planned (default) time of opening is indicative of the use of feedforward control rather than feedback control since the time of opening was around 0.8 s.

For the $2\frac{1}{2}$ somersault dives the arm angle at the time of maximum arm variation was positively correlated with the orientation angle at the earlier time of maximum hip variation (Table 7), indicating that the arms made a second adjustment. If the orientation angle was large then so was the arm angle, again increasing the moment of inertia and slowing the somersault. Alternatively this may be viewed as an earlier raising of the arms when the orientation angle at the time of hip extension was greater than expected. This adjustment may be expected to have arisen from the use of feedback control since the time between maximum hip variation and maximum arm angle variation was around 0.27 s.

The final hip angle of the $2\frac{1}{2}$ somersault dives was positively correlated with the orientation angle at the earlier time of maximum arm angle variation (Table 7), indicating that a final adjustment was made using the hip angle. If the orientation angle was low then the hip angle remained low so as to compensate. Again this adjustment may be expected to have arisen from the use of feedback control since the time difference was around 0.13 s. Thus all three joint angle adjustments make sense in terms of mechanics.

Within the flight phase the joint angle time histories had periods of relative invariance and also periods of increased variability which may be considered to be examples of functional variability. The concept of functional variability is where the presence of more variability plays a functional role in stabilising other aspects of the movement or increasing the consistency of the movement outcome (Hamill, van Emmerik, Heiderscheit, & Li, 1999; van Emmerik, Hamill, and McDermott, 2005). Increased variability may be associated with expertise and an indication of increased adaptability as Wilson et al. (2008) found for triple jumpers. Similarly, in diving, Barris, Farrow & Davids (2014) described the functional role of movement variability as the adaptability of springboard divers under different training conditions. It was found that by training with induced variability that divers indeed demonstrated more variability in the hurdle phase but they also became more consistent in terms of reducing the number of dives aborted (balked). In other words, it appeared that the divers had learned to cope with the induced variability by making the appropriate adjustments. However, care should be taken when identifying increased movement variability and attributing it to higher levels of ability or adaptability, since it must be

established how the observed variability is related to the success of the task, i.e. determine the mechanism and its function. In the present study there is a clear link between the increased variability in hip and arm angles during flight, the rotation potential at takeoff, and the mechanics of such joint angle adjustments.

The exact nature of the sensory feedback on which the adjustments were based remains unknown. However, there is a strong indication that it is based on information regarding the angular momentum and time of flight of the dive (Table 5). In the forward pike dive the water can be kept in view for the whole of the flight phase and so visual information may contribute to the estimation of somersault rotation, angular velocity and flight time. In the forward 2½ somersault pike the water can be viewed continuously from the extension from the pike to water entry and so visual information may be used to time the final arm and hip corrections based upon the amount of somersault rotation. While somersaulting in the piked position it is likely that the somersault rate is estimated from the otolith and semicircular canal information and that this governs the timing of the extension from the pike.

In summary there was evidence that the diver performed the early flight in a given way for a given dive number but timed the extension from the pike position to adjust for variations in angular momentum and time of flight. In the case of the 2½ somersault pike dive subsequent adjustments were made using arm and hip angle changes in order to obtain a suitable entry angle. The variability seen in the diver's movements was therefore not random, and performed a functional role in ensuring a consistent entry into the water. The adjustments were performed through feedforward or feedback control, since the actions were related to events occurring earlier in the flight phase. Although other divers might make adjustments somewhat differently the need for adjustment will remain if a good performance is to be achieved since, without such adjustment, the orientation angle at entry will be greatly affected by small variations at takeoff.

REFERENCES

- Barris, S., Farrow, D., & Davids, K. (2014). Increasing functional variability in the preparatory phase of the takeoff improves elite springboard diving performance. *Research Quarterly for Exercise and Sport*, 85, 97-106.
- Bartlett, R., Wheat, J., & Robins, M. (2007). Is movement variability important for sports biomechanists? *Sports Biomechanics*, 6, 224–243.
- Bowerman, B.L., & O'Connell, R.T. (1990). *Linear statistical models: An applied approach* (2nd ed.) Belmont, CA: Duxbury.
- Field, A. (2013). *Discovering statistics using IBM SPSS statistics*. (4th ed.) Thousand Oaks, CA: Sage.
- Hamill, J., van Emmerik, R.E.A., Heiderscheit, B.C., & Li, L. (1999). A dynamical systems approach to lower extremity running injuries. *Clinical Biomechanics*, 14, 297–308.
- Hiley, M. J., & Yeadon, M.R. (2008). Optimisation of high bar circling technique for consistent performance of a triple piked somersault dismount. *Journal of Biomechanics* 41, 1730-1735.

- Hiley, M.J., Zuevsky, V., & Yeadon, M.R. (2013). Is skilled technique characterised by high or low variability – An analysis of high bar giant circles? *Human Movement Science* 32, 171-180.
- Hiley, M. J., & Yeadon, M.R. (2016). The role of functional variability in a whole body co-ordinated movement – application to high bar giant circles. *Human Movement Science*, 49, 95-103.
- Jagacinski, R.J., & Flach, J.M. (2003). Control theory for humans: Quantitative approaches to modeling performance. Mahwah, NJ: Lawrence Erlbaum Associates, (Chapter 2).
- King, M.A., & Yeadon, M.R. (2004). Maximising somersault rotation in tumbling. *Journal of Biomechanics*, 37, 471-477.
- Lambert, J.D. (1973). Computational methods in ordinary differential equations, pp. 130-135. New York: Wiley.
- Latash, M.L. (1998). Neurophysiological basis of movement. Champaign, IL: Human Kinetics, (Chapter 12).
- Menard, S. (1995). Applied logistic regression analysis. Sage university paper series on quantitative applications in the social sciences, pp. 07–106. Thousand Oaks, CA: Sage.
- Miall, R.C., & Wolpert, D.M. (1996). Forward models for physiological motor control. *Neural Networks*, 9, 1265-1279.
- Miller, D.I., & Munro, C.F. (1985). Greg Louganis' springboard takeoff: II. Linear and angular momentum considerations. *International Journal of Sport Biomechanics*, 1, 288-307.
- Miller, D.I., Zecevice, A., & Taylor, G.W. (2002). Hurdle preflight in springboard diving: A case of diminishing returns. *Research Quarterly for Exercise and Sport*, 73, 134-145.
- Myers, R. (1990). Classical and modern regression with applications (2nd ed.). Boston, MA: Duxbury.
- Newell, K.M., & Corcos, D.M. (1993). Issues in variability and motor control. In K. M. Newell & D.M. Corcos (Eds.), *Variability and motor control*. Champaign, IL: Human Kinetics.
- Preatoni, E., Hamill, J., Harrison, A. J. Hayes, K., Van Emmerik, R. E. A., Wilson, C., & Rodano, R. (2013). Movement variability and skills monitoring in sports. *Sports Biomechanics*, 12, 69-92.
- van Beers, R.J., Haggard, P., & Wolpert, D.M. (2004). The role of execution noise in movement variability. *Journal of Neurophysiology*, 91, 1050-1063.
- van Emmerik, R.E.A., Hamill, J., & McDermott, W.J. (2005). Variability and coordinative function in human gait. *Quest*, 57, 102-123.
- Wilson, C., Simpson, S.E., Van Emmerik, R.E.A., & Hamill, J. (2008). Coordination variability and skill development in expert triple jumpers. *Sports Biomechanics*, 7, 2–9.
- Wolpert, D.M. (1997). Computational approaches to motor control. *Trends in Cognitive Sciences*, 1, 209-216.
- Yeadon, M.R. (1990a). The simulation of aerial movement -- I. The determination of orientation angles from film data. *Journal of Biomechanics*, 23, 59-66.

- Yeadon, M.R. (1990b). The simulation of aerial movement -- II. A mathematical inertia model of the human body. *Journal of Biomechanics*, 23(1), 67-74.
- Yeadon, M.R. (1990c). The simulation of aerial movement – III. The determination of the angular momentum of the human body. *Journal of Biomechanics*, 23, 75-83.
- Yeadon, M.R., Atha, J., & Hales, F.D. (1990). The simulation of aerial movement - IV: A computer simulation model. *Journal of Biomechanics*, 23, 85-89.
- Yeadon, M.R., & Hiley, M.J. (2014). The control of twisting somersaults. *Journal of Biomechanics*, 47, 1340 – 1347.
- Yeadon, M.R., & Mikulcik, E.C. (1996). The control of non-twisting somersaults using configuration changes. *Journal of Biomechanics*, 29, 1341–1348.
- Yeadon, M.R., & Trewartha, G. (2003). Control strategy for a hand balance. *Motor Control*, 7, 411–430.