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

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ABSTRACT

In springboard diving consistency of body orientation at water entry is necessary for a good dive and is likely to be dependent on the consistency of conditions at takeoff. The aim of the present study was to investigate whether a diver modifies his technique from dive to dive during the board contact phase in order to be more consistent at takeoff in one metre springboard forward dives. Two-dimensional video analysis was used to calculate orientation and configuration angles of 12 forward pike dives and 12 forward 2½ somersault pike dives, performed by an international diver. A computer simulation model of a diver and springboard during board contact was used to obtain matching simulations of the performances and to calculate the rotation potential (angular momentum x flight time) for each dive. Simulations were used to determine the variation in conditions at maximum board depression arising from variation in touchdown conditions, and the variation in takeoff conditions arising from the variability in conditions at maximum board depression. A comparison of the simulated and performance variations implied that adjustments were made during the board contact phase for both the pike dives and the 2½ somersault pike dives. In the board depression phase, adjustments reduced the variability in the mass centre horizontal velocity at the lowest point. In the board recoil phase, adjustments reduced the variability in the horizontal velocity and rotation potential at takeoff.

Keywords: springboard diving, computer simulation; motor control

INTRODUCTION

A springboard dive can be divided into (a) the hurdle phase, (b) the contact phase, and (c) the flight phase (Figure 1: A-C, C-E, E-F). The mechanical objectives of the hurdle and contact phases are: the generation of sufficient angular momentum, vertical velocity, and horizontal velocity at takeoff in order to achieve the required rotation and height in the flight phase while travelling safely away from the board. In the subsequent flight phase the diver must complete the technical requirements of the dive (somersaults and twists) as well as ensuring the correct orientation angle on entry into the water (Miller & Munro, 1985; Sayyah, Hiley, King & Yeadon, 2018). The consistency of the entry angle depends on the variability of the takeoff conditions and the extent to which adjustments are made to configurational changes in the flight phase (Sayyah et al., 2018). Elite performance in sport may be characterised as having great consistency (Hiley & Yeadon, 2016), particularly in terms of performance outcome (Preatoni et al., 2013). Despite consistency in performance outcome, it is not unusual to see variability in the actions responsible for producing the outcome (Wilson, Simpson, Van Emmerik & Hamill, 2008; Sayyah et al., 2018; Bartlett, Wheat & Robins, 2007; Preatoni et al., 2013; Newell & Corcos, 1993).

Figure 1. One metre springboard forward pike dive: A = hurdle touchdown, B = hurdle takeoff, C = hurdle landing, D = maximum board depression, E = takeoff, F = water entry, (A to C) = hurdle, (C to D) = board depression, (D to E) = board recoil, (E to F) = flight phase.

Variability in an athlete's actions may be a result of a number of factors (van Beers, Haggard & Wolpert, 2004) that will be dependent on the nature and duration of the task. In the throwing of a dart there is insufficient time to make adjustments once the throw has started and consistency in performance is achieved via consistency of execution of a pre-planned (open loop control) technique (Smeets, Frens & Brenner, 2002). Such technique may be optimised by training and become more robust to variations in execution by operating in the most tolerant region of the solution space and by maximising the available covariation (Cohen & Sternad, 2009). When receiving a tennis serve there is insufficient time to modify pre-planned return technique once the ball has been struck. The receiver therefore pre-plans modifications (Jagacinski & Flach, 2003) of return technique (feedforward control) based on cues taken from the server's actions prior to ball contact (Wolpert, 2007; Goulet, Bard & Fleury, 1989). Balancing in a handstand is a longer duration, ongoing task where the gymnast will make continual adjustments by modifying the wrist torque in response to perceived movements of the mass centre (Blenkinsop, Pain & Hiley, 2017). In this situation the gymnast is making use of feedback control (Jagacinski & Flach, 2003). The variability of technique in each of the previous examples has a component of 'functional variability' which is variation that plays a role in stabilising or ensuring low variability in the performance outcome (Preatoni et al., 2013; Hamill, van Emmerik, Heiderscheit & Li, 1999; Bartlett et al., 2007).

In the flight phase of acrobatic movements there is ample time (more than 1 s) to make adjustments using feedforward control or feedback control (Yeadon & Mikulcik, 1996; Yeadon & Hiley, 2014). In repeated performances of forward $2\frac{1}{2}$ somersault pike dives, Sayyah et al. (2018) found that three sequential adjustments were made during flight using feedforward and feedback control to ensure the diver had the correct orientation on entry into the water. In the contact phase prior to the flight phase of acrobatic movements there is much less time available for adjustments: 0.1 s in

tumbling (King & Yeadon, 2004); 0.4 s in trampolining (Blajer & Czaplicki, 2003); 0.5 s in springboard diving (Miller, Zecevic & Taylor, 2002). In a springboard diving takeoff the question arises whether a fixed technique is used (open loop control) or whether modifications to takeoff technique are pre-planned prior to touchdown (feedforward control) or whether adjustments are made based on information received during takeoff (feedforward or feedback control).

Angular momentum is developed for forward rotating dives primarily during the recoil phase of springboard contact (Figure 1: D-E) using hip flexion (King, Kong & Yeadon, 2019) which results in a backwards reaction force of the springboard on the feet. This horizontal reaction force produces a torque about the mass centre increasing the forward angular momentum. The reaction force also slows the mass centre horizontal velocity. In order that the diver travels a safe distance away from the board during flight the horizontal mass centre velocity at takeoff must be of appropriate magnitude.

Although technique in the contact phase of springboard diving is developed using repeated attempts, the coordinated movements are not identical from trial to trial due to errors in: the selection of motor commands, sensory information, and execution (van Beers et al., 2004; Bartlett et al., 2007; Cohen & Sternad, 2009). It might be expected that elite divers will be very consistent in the springboard touchdown conditions at the end of the hurdle phase. If open loop control is used the joint angle variability during springboard contact will be predominantly a function of the variability at touchdown. On the other hand if feedback or feedforward control is used, the joint angle variability will be functional in that it will arise mainly from technique adjustments made in each individual dive. Sayyah et al. (2018) found that rotation potential at takeoff (angular momentum multiplied by flight time) and mass centre horizontal velocity had low variability. Therefore, the aim of the present study is to investigate whether low variability in rotation potential and horizontal velocity at takeoff can be attributed to low variability at springboard touchdown or whether a diver makes functional configurational adjustments during contact to reduce the variability at takeoff.

METHOD

A case study of a diver repeating the same dive was conducted to measure variability in technique during the board contact phase in springboard diving. A diver-specific simulation model was applied to investigate whether configurational variability during the contact phase is functional by comparing (a) the variability in conditions at maximum board depression arising from variation in touchdown conditions, and (b) the variation in rotation potential and horizontal velocity at takeoff arising from the variability in conditions at maximum board depression, with the actual variation in the repeated trials.

Data collection and analysis

One male international diver (age 21 years, mass 70 kg, height = 1.8 m) gave informed consent to participate in the study which was approved by the university's ethics committee. 12 forward pike dives (101B) and 12 forward 2½ somersault pike dives (105B) from the one-metre springboard were recorded using a Fastec TS3 high speed camera operating at 250 Hz. In each dive 10 body landmarks (right wrist, elbow, shoulder, hip, knee, ankle, heel, ball and toes, and the centre of the head) and the end of the springboard were digitised from the hurdle landing until the diver entered the water. A two-dimensional direct linear transformation method (Sayyah et al., 2018)

was used to reconstruct the projections of the body landmarks on a vertical plane through the right hip when standing on the springboard. The coordinate data were then used to calculate the springboard's linear and angular displacement, the diver's orientation and joint angle time histories (Yeadon, 1990a) and these were fitted using quintic splines (Wood & Jennings, 1979) to provide continuous data for use in simulations. Diver-specific segmental inertia parameters were calculated from anthropometric measurements using a mathematical inertia model (Yeadon, 1990b) and were used along with the splined data to calculate mass centre velocity and whole-body angular momentum (Yeadon, 1990c). Body configuration was specified by arm elevation angle between upper arm and trunk, elbow angle between forearm and upper arm, neck angle between head and trunk, hip angle between thigh and trunk, knee angle between shank and thigh, ankle angle between foot and shank, and ball angle at the metatarsal-phalangeal joint. Whole body orientation to the vertical was calculated as a weighted mean of trunk and leg orientations with the trunk angle weighted twice as much as the leg angle (King et al., 2019). A pseudo data set comprising the average of values in adjacent frames on either side of each data point was used to assess the precision of arm and hip angles as 0.4° .

Simulation model

A planar 8-segment angle-driven diver-specific simulation model of a diver and springboard (Figure 2) described in Yeadon, Kong and King (2006) was used to compare (a) the variability in conditions at maximum board depression arising from variation in touchdown conditions, and (b) the variation in rotation potential and horizontal velocity at takeoff arising from the variability in conditions at maximum board depression, with the actual variation in the repeated trials. The model segments were: head, upper arm, lower arm, trunk, thigh, shank and a two-segment foot. Wobbling masses were included within the trunk, thigh and shank segments to represent soft tissue movement during the landing on the springboard (Figure 2). The foot-springboard interface was modelled using three identical pairs of parallel and perpendicular damped springs acting at the toe, ball and heel. The springboard was modelled as a linear vertical spring with horizontal and rotational movement expressed as functions of vertical displacement (Yeadon et al., 2006). The input to the model comprised: 1) the initial conditions at touchdown: the springboard vertical displacement and velocity, the diver's foot distance from the end of the board, mass centre velocity, trunk orientation and angular velocity, and 2) seven joint angle time histories. The output of the model comprised the time histories of the springboard displacement, body orientation, mass centre velocity and whole-body angular momentum about the mass centre. Takeoff occurred when the board reached its neutral unloaded position.

Matching simulations of each of the recorded 12 forward pike dives and 12 forward $2\frac{1}{2}$ somersault pike dives were determined by varying parameters specifying the wobbling masses, the foot-springboard interface, and the springboard to minimise a difference score between simulation and performance using the simulated annealing algorithm (Corana, Marchesi, Martini & Ridella, 1987). The difference score was the average of equally weighted differences of trunk angle, horizontal velocity, vertical velocity, board depression, time of contact, and angular momentum with trunk angle in degrees and the remainder expressed as percentages (Yeadon et al., 2006). Mean matching difference scores for the pike dives and the $2\frac{1}{2}$ somersault pike dives were 2.5% and 2.7% respectively.

Figure 2. Planar simulation model of a springboard and an 8-segment diver. Wobbling masses are included in the trunk, thigh and shank segments, and visco-elastic spring-dampers are acting at the heel, ball and toe representing the foot-springboard interface.

The rotation potential during flight was calculated as the product of flight time and angular momentum normalised using the moment of inertia of the body to give the equivalent number of straight somersaults (Hiley & Yeadon, 2008). The rotation potential at takeoff was defined to be the rotation potential of the flight phase plus the initial body orientation at takeoff expressed in somersaults.

Simulations with variations of the initial conditions

For each of the two dives the variability of mass centre horizontal velocity and trunk angular velocity at the lowest point was calculated from the 12 matching simulations. This was compared with the lowest point variability determined from simulations of perturbed initial touchdown conditions. The initial touchdown values of mass centre horizontal velocity, vertical velocity and trunk angular velocity were allowed to vary by $\pm$ one standard deviation as calculated from the 12 trials, giving eight possible combinations. For each of the 12 matching simulations the eight combined perturbations of the three initial variables were used to drive the perturbed simulations, and the standard deviation of the eight values of horizontal velocity and trunk angular velocity at the lowest point was calculated. From these a mean standard deviation was calculated for the 12 trials for horizontal velocity and angular velocity.

For each of the two dives the variability in rotation potential and horizontal velocity at takeoff was calculated from the 12 matching simulations. This was compared with the variability at takeoff determined from simulations using perturbed lowest point conditions. The lowest point values of mass centre horizontal velocity and trunk angular velocity were each allowed to vary by $\pm$ one standard deviation as calculated from the 12 trials, giving four possible combinations. For each of the 12 matching simulations the four combined perturbations were used to drive the perturbed simulations, and the standard deviation of the four values of rotation potential was calculated. From these a mean standard deviation for rotation potential was calculated for the 12 trials. The same was done for horizontal velocity at takeoff.

Statistical analysis

All data used in the statistical analyses were assessed for normality using the Shapiro-Wilk test (Field, 2009) and were found to be normally distributed. For each of the two dives a two-tailed one-sample t-test (IBM SPSS Statistics for Windows, version 23.0, Armonk, NY: IBM corp.) was used to investigate whether the mean standard deviation in the horizontal velocity at the lowest point, as determined using the simulations with perturbed initial touchdown conditions, was different from the standard deviation of the lowest point horizontal velocity from the video analysis. A significant result would indicate that adjustments had been used in the board depression phase that affected the lowest point horizontal velocity. This was repeated for the trunk angular velocity at the lowest point.

For each of the two dives a one-tailed one-sample t-test was used to investigate whether the mean standard deviation of the rotation potential at takeoff for the simulations with perturbed lowest point conditions was greater than the standard deviation of the rotation potential at takeoff of the matching simulations. A significant result would indicate that adjustments had been used in the board recoil phase to control the rotation potential at takeoff. A similar analysis was used to investigate whether the mean standard deviation of the horizontal velocity at takeoff for the simulations with perturbed lowest point conditions was greater than the standard deviation of the horizontal velocity at takeoff calculated from the video analysis.

RESULTS

Table 1. Touchdown and takeoff angles, mass centre velocities, rotation potential and flight time of 12 forward pike dives and 12 forward 2½ somersault pike dives

	pike dive		2½ somersault	
	touchdown	takeoff	touchdown	takeoff
hip (°)	92.6 ± 5.3	164.2 ± 2.8	94.1 ± 3.4	110.9 ± 4.2
knee (°)	98.6 ± 2.4	176.8 ± 1.9	99.4 ± 2.4	177.5 ± 1.3
arm elevation (°)	-33.2 ± 4.9	180.9 ± 3.2	-15.6 ± 3.2	100.3 ± 5.7
orientation (°)	14.9 ± 1.6	13.4 ± 0.8	16.8 ± 0.9	49.7 ± 2.7
horizontal velocity (ms ⁻¹)	0.25 ± 0.05	0.90 ± 0.07	0.37 ± 0.06	0.90 ± 0.12
vertical velocity (ms ⁻¹)	-4.8 ± 0.05	5.85 ± 0.08	-4.9 ± 0.04	5.19 ± 0.08
takeoff time (ms)		446 ± 9.2		422 ± 8.7
rotation potential (ss)		0.348 ± 0.017		1.330 ± 0.031

The standard deviations of the orientation angle (1° - 3°), joint angles (1° - 6°), and mass centre velocities (< 2% of resultant velocity) show that the diver was quite consistent at touchdown and takeoff (Table 1). The variation in board contact time (2%) and the rotation potential at takeoff (2% - 5%) were also relatively small. The standard deviation time histories of the joint angles during the takeoff phase of 12 forward pike dives and 12 forward 2½ somersault pike dives show that the hip and knee angles reached their peaks during the board recoil phase and then decreased towards takeoff (Figure 3). The arm angle variability for the pike dives

peaked during the board depression phase (Figure 1: C-D) while that of the $2\frac{1}{2}$ somersault pike dives had two peaks, one during board depression and another during board recoil (Figure 1: D-E). For the pike dives the orientation angle variability peaked just before the lowest point was reached and then remained low ($< 1^\circ$) until takeoff. In contrast, for the $2\frac{1}{2}$ somersault pike dives, the peak orientation angle variability was reached at takeoff and increased steadily throughout the board recoil phase (Figure 3).

Figure 3. Mean (thick black line) and standard deviation (shaded grey) time histories of orientation, hip, knee and arm angles during the takeoff phase of recorded performances of (a) 12 forward pike dives and (b) 12 forward $2\frac{1}{2}$ somersault pike dives. The vertical dashed line shows the average time at mass centre lowest point.

The mean standard deviation of the horizontal mass centre velocity (0.129 ms^{-1}) at the lowest point arising from the pike dive simulations with touchdown perturbations (Table 2) was greater than ($p < 0.001$) the standard deviation obtained from the video analysis (0.031 ms^{-1}). The mean standard deviation of the horizontal mass centre velocity (0.197 ms^{-1}) at the lowest point arising from the $2\frac{1}{2}$ somersault pike dive simulations with touchdown perturbations (Table 2) was again greater than ($p < 0.001$) the standard deviation obtained from the video analysis (0.047 ms^{-1}). These results imply that the diver made adjustments during board depression to control the horizontal velocity.

The mean standard deviation of the trunk angular velocity (0.128 s^{-1}) at the lowest point arising from the perturbed pike dive simulations (Table 2) was less than ($p < 0.001$) the standard deviation obtained from the video analysis (0.347 s^{-1}). The mean standard deviation of the trunk angular velocity (0.199 s^{-1}) at the lowest point arising from the perturbed $2\frac{1}{2}$ somersault pike dive simulations (Table 2) was not significantly different from ($p = 0.2$) the standard deviation obtained from the video analysis (0.237 s^{-1}).

Table 2. Lowest point conditions for performance and for perturbed simulations

		pike dive		$2\frac{1}{2}$ somersault	
		mean	SD	mean	SD
horizontal velocity [ms^{-1}]	video analysis	0.551	0.031	0.864	0.047
horizontal velocity [ms^{-1}]	perturbated simulations	0.472	0.129	0.832	0.197
angular velocity [s^{-1}]	video analysis	1.612	0.347	0.776	0.237
angular velocity [s^{-1}]	perturbated simulations	1.628	0.128	0.535	0.199

Note: perturbed standard deviation is the mean value for the 12 trials

When the simulations of the pike dives were started with perturbations from the lowest point of the mass centre the mean standard deviation of the rotation potential at takeoff (0.066 ss) for the pike dives (Table 3) was greater than ($p = 0.002$) the standard deviation of the matching simulations (0.017 ss). For the $2\frac{1}{2}$ somersault pike dives the mean standard deviation of the rotation potential at takeoff (0.124 ss) calculated from the lowest point perturbed simulations (Table 3) was also greater than ($p = 0.017$) the standard deviation of the matching simulations (0.031 ss). These results imply that the diver made adjustments during the board recoil phase to control the rotation potential at takeoff.

The mean standard deviation of the horizontal mass centre velocity (0.282 ms^{-1}) at takeoff arising from the pike dive simulations with lowest point perturbations (Table 3) was greater than ($p < 0.001$) the standard deviation obtained from the video analysis (0.071 ms^{-1}). The mean standard deviation of the horizontal mass centre velocity (0.233 ms^{-1}) at the lowest point arising from the $2\frac{1}{2}$ somersault pike dive simulations with lowest point perturbations (Table 3) was again greater than ($p < 0.001$) the standard deviation obtained from the video analysis (0.124 ms^{-1}). These results imply

that the diver made adjustments during board recoil to control the horizontal velocity at takeoff.

Table 3. Takeoff conditions for performance and for perturbed simulations

		pike dive		2½ somersault	
		mean	SD	mean	SD
rotation potential [ss]	matched simulations	0.348	0.017	1.330	0.031
rotation potential [ss]	perturbated simulations	0.344	0.066	1.227	0.124
horizontal velocity [ms ⁻¹]	video analysis	0.903	0.071	0.901	0.124
horizontal velocity [ms ⁻¹]	perturbated simulations	0.814	0.282	1.147	0.233

Note: perturbed standard deviation is the mean value for the 12 trials

DISCUSSION

The aim of this study was to investigate whether the low variability in rotation potential and mass centre horizontal velocity at takeoff can be attributed to the low variability at touchdown or whether a diver makes functional configurational adjustments during board contact to reduce the variability at takeoff. A single subject case study design of repeated trials of the same dive was conducted to measure variability in technique during the board contact phase. The statistical analyses showed that adjustments were made during the first half of board contact reducing the variation in the mass centre horizontal velocity at the lowest point. For the forward pike dives there was a concomitant increase in the variation of trunk angular velocity at the lowest point. This might be a consequence of changing the hip and knee angles to induce a horizontal reaction force at the feet in order to adjust the horizontal velocity in that the trunk angle will also change. For the 2½ pike dives, however, there was no significant difference between the variance in trunk angular velocity estimated from perturbed simulations and the actual variance from the performances. The control mechanism for such joint angle changes is likely to be feedforward adjustments based on an estimation of the touchdown conditions during the hurdle flight (McNitt-Gray, Hester, Mathiyakom & Munkasy, 2001) together with feedback adjustments after touchdown similar to those made in standing balance (Blenkinsop et al., 2017). This is supported by the joint angle variability during the board depression phase in which the variability of the knee, hip and arm angles each increase with the arm angle variability reaching a peak during this phase for both dives (Figure 3).

During the board recoil phase configurational adjustments were made reducing the variation in both rotation potential and mass centre horizontal velocity at takeoff. The primary mechanism for generating angular momentum during the board recoil phase is hip flexion which reached maximum variability shortly after the lowest point for both dives and then decreased towards takeoff. Since this hip flexion will also slow the mass centre horizontal velocity, the velocity at the lowest point will need to be sufficiently high. The mechanism for generating vertical velocity is the timing of the knee extension and this showed maximum variation late in the recoil phase for the 2½

pike somersault dives and showed large variation until late in the recoil phase for the pike dives. The control mechanism for these adjustments in the board recoil phase is likely to be feedforward rather than feedback with a modification to the pre-planned joint angle configurational time histories being based on the information received during the board depression phase. As the recoil phase is approximately 250 ms there will be insufficient time to make significant adjustments with feedback control based on the conditions at the lowest point. Since there are high levels of variability in hip and knee angles just after the lowest point it is more likely that the diver makes an estimate of the horizontal velocity at the lowest point during the depression phase and modifies the recoil phase based upon this (i.e. performs the recoil phase under feedforward control). The contribution of the vertical reaction force to the production of forward rotation is dependent upon the horizontal mass centre position relative to the feet and therefore upon the mass centre horizontal velocity. The variation in horizontal velocity at takeoff was almost twice as large for the $2\frac{1}{2}$ somersault dives compared to the pike dives (Tables 1, 3). This is probably a consequence of having to produce greater angular momentum using greater and more variable horizontal reaction forces with the diving board. The mean horizontal velocity at the lowest point for the $2\frac{1}{2}$ pike dives was much larger than that of the pike dives (0.86 ms^{-1} versus 0.55 ms^{-1} , Table 2) presumably since greater hip flexion is used to generate greater angular momentum, resulting in greater retardation of horizontal velocity. The horizontal velocities of the pike dives and $2\frac{1}{2}$ somersault pike dives at takeoff were similar at 0.90 ms^{-1} .

The variation in each joint angle for the pike dives was smallest when each joint angle plateaued at around 180° just prior to takeoff (Figure 3). For the $2\frac{1}{2}$ somersault dives the knee angle and arm angle variation also reached minima as the joint angles approached 180° , at takeoff in the case of the knee angle and shortly after the lowest point for the arm angle. The time history of hip angle variation was similar to the hip angle time history as was the case for the orientation angle and its variation for both dives (Figure 3).

The implications of potential limitations will now be considered. The precision of the arm and hip angles calculated via manual digitisation was assessed as 0.4° . Since this is relatively small compared to the variation in the 12 trials, it will have had only a small effect. The accuracy of the matched simulations (2.5%, 2.7%) may be considered to be sufficiently good that the simulated variations provide a reasonable representation. The main limitation is that a single case study was considered so that there is the question of whether it is representative of other elite springboard divers. It may be expected that future case studies will also show that adjustments are made in the board depression and recoil phases during takeoff.

The concept of functional variability refers to variability that plays a role in stabilising other aspects of the movement or increasing the consistency of the performance outcome (Hamill et al., 1999; van Emmerik, Hamill & McDermott, 2005). It is sometimes also referred to as an athlete's ability to adapt successfully to the environment (Barris, Farrow & Davids, 2014). By training with induced variability in the hurdle phase of a springboard dive, Barris et al. (2014) found that divers not only demonstrated more variability in this phase but also became more consistent in terms of reducing the number of aborted dives. The divers had learned the appropriate adjustments to make in order to cope with the induced variability. This suggests that elite divers are able to make accurate assessments of performance parameters and modify their movement patterns appropriately. Sayyah et al. (2018) demonstrated that,

in the flight phase of 1 m springboard dives, divers most likely plan the aerial phase in advance (Miall & Wolpert, 1996) based on the expected linear and angular momenta at take-off. The increased variability found in the hip and arm angles later in flight was a result of the diver re-evaluating the current state of the movement (Miall & Wolpert, 1996; Wolpert, 1997), and making changes to the planned movements to ensure the correct orientation on water entry. In the present study a comparison of the simulated and performance variations implied that functional adjustments were made during the board contact phase for both the pike dives and the 2½ somersault pike dives. In the board depression phase, adjustments reduced the variability in the mass centre horizontal velocity at the lowest point. In the board recoil phase, adjustments reduced the variability in the rotation potential and mass centre horizontal velocity at takeoff. In both cases it is likely that there was a strong component of feedforward control which lead to the functional variability in technique.

CONFLICT OF INTEREST STATEMENT

There are no issues of conflict of interest arising from the personal or professional associations of the authors

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.
- Blajer, W., & Czaplicki, A. (2003). Contact modeling and identification of planar somersaults on the trampoline. *Multibody System Dynamics*, 10, 289-312.
- Blenkinsop, G.M., Pain, M.T.G., & Hiley, M.J. (2017). Balance control strategies during perturbed and unperturbed balance in standing and handstand. *Royal Society Open Science*, 4, 161018.
- Cohen, R.G., & Sternad, D. (2009). Variability in motor learning: Relocating, channeling and reducing noise. *Experimental Brain Research*, 193, 69–83.
- Corana, A., Marchesi, M., Martini, C. & Ridella, S. (1987). Minimizing multimodal functions of continuous variables with the "Simulated Annealing" algorithm. *ACM Transactions on Mathematical Software*, 13, 262-280.
- Field, A.P. (2009). *Discovering statistics using SPSS*. London, England: SAGE.
- Goulet, C., Bard, C., & Fleury, M. (1989). Expertise differences in preparing to return a tennis serve: A visual information processing approach. *Journal of Sport & Exercise Psychology*, 11, 382-398.
- 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. and 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, (Chapters 2, 20).

- King, M.A., & Yeadon, M.R. (2004). Maximising somersault rotation in tumbling. *Journal of Biomechanics*, 37, 471-477.
- King, M.A., Kong, P.W., & Yeadon, M.R. (2019). Maximising forward somersault rotation in springboard diving. *Journal of Biomechanics*, 85, 157-163.
- McNitt-Gray, J.L., Hester, D.M.E., Mathiyakom, W., & Munkasy, B.A. (2001). Mechanical demand and multijoint control during landing depend on orientation of the body segments relative to the reaction force. *Journal of Biomechanics*, 34, 1471-1482.
- 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., Zecevic, A. & Taylor, G.W. (2002). Hurdle pre-flight in springboard diving: a case of diminishing returns. *Research Quarterly for Exercise and Sport*, 73, 134-145.
- Newell, K.M. & Corcos, D.M. (1993). Issues in variability and motor control. In K.M. Newell and D.M. Corcos (eds) *Variability and motor control*. Human Kinetics. Champaign, IL.
- 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.
- Sayyah, M., Hiley, M.J., King, M.A., & Yeadon, M.R. (2018). Functional variability in the flight phase of one metre springboard forward dives. *Human Movement Science*, 59, 234-243.
- Smeets, J.B.J., Frens, M.A., & Brenner E. (2002). Throwing darts: timing is not the limiting factor. *Experimental Brain Research*, 144, 268-274.
- 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.
- Wolpert D.M. (2007). Probabilistic models in human sensorimotor control. *Human Movement Science*, 26, 551-524.
- Wood, G.A., & Jennings, L.S. (1979). On the use of spline functions for data smoothing. *Journal of Biomechanics*, 12, 477-479.
- 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, 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., & Hiley, M.J. (2014). The control of twisting somersaults. *Journal of Biomechanics*, 47, 1340 – 1347.

- Yeadon, M.R., Kong, P.W., & King, M.A. (2006). Parameter determination for a computer simulation model of a diver and a springboard. *Journal of Applied Biomechanics*, 22, 167-176.
- Yeadon, M.R., & Mikulcik, E.C. (1996). The control of non-twisting somersaults using configuration changes. *Journal of Biomechanics*, 29, 1341–1348.