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The limits of aerial and contact techniques for producing twist in reverse 1½ somersault dives

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ABSTRACT

An angle-driven computer simulation model of aerial movement was used to determine the maximum amount of twist that can be produced in a reverse 1½ somersault dive from a three-metre springboard using various aerial and contact twisting techniques. The segmental inertia parameters of an elite springboard diver were used in the simulations and lower bounds were placed on the durations of arm and hip angle changes based on recorded performances of twisting somersaults. A limiting dive was identified as that producing the largest possible odd number of half twists. Simulations of the limiting dives were found using simulated annealing optimisation to produce the required amounts of somersault, tilt and twist after a flight time of 1.5 s. Additional optimisations were then run to seek solutions with the arms less adducted during the twisting phase. It was found that the upper limits ranged from 3½ to 5½ twists with arm abduction ranges lying between 8° and 23°. Similar results were obtained when the inertia parameters of two other springboard divers were used. It may be concluded that a reverse 1½ somersault dive using aerial asymmetrical arm and hip movements to produce 5½ twists is a realistic possibility. To accomplish this limiting dive the diver needs to be able to coordinate the timing of configurational changes with the progress of the twist with a precision of 10 ms or better.

Keywords: computer simulation, aerial movement, diving, twisting

INTRODUCTION

For the past sixty years there has been controversy as to whether the twist in springboard diving is taken from the board (contact twist) or initiated after takeoff (aerial twist). In the case of forward 2½ somersault dives in which the twist starts in the second somersault it is clear that aerial twist is used. In contrast backward and reverse somersaulting dives with twist typically show an early twist which may indicate that an element of contact twist is used. According to rule D8.4.6 for judging dives: “In dives with twist, the twisting shall not be manifestly done from the springboard or platform” (FINA, 2017). This suggests that contact twist is in use and that its contribution should be limited.

Various techniques have been proposed for producing aerial twist and contact twist. The use of asymmetrical arm movements for producing aerial twist in a somersault by tilting the twist axis out of the vertical somersault plane was shown to be viable by Frolich (1979) and Pike (1980) using computer simulation models. Rackham (1970) and Batterman (1974) advocated torsion of the chest in the direction of twist when the hips are flexed, causing the legs to swing in the opposite direction so that when the body extends it will be tilted. Yeadon (1993a, 1993b) used a rigid body model and models with two or three segments to determine the resulting twist from movements of the arms, the chest, and the whole body during the contact phase. By considering contributions to the tilt angle Yeadon (1993a, b, c, d) investigated the contributions of contact and aerial twisting techniques in performances of twisting somersaults using a rigid body model of aerial movement together with an 11-segment computer simulation model. In an analysis of eight reverse 1½ somersault dives with 2½ twists it was found that aerial asymmetries of arms, chest and hips as well as contact techniques all made contributions to the tilt angle (Yeadon, 1993e).

It is important to distinguish between visible tilt away from the vertical plane through the centre line of the diving board and mechanical tilt away from the plane perpendicular to the angular momentum vector (Yeadon, 1993b). In the case of aerial twist the angular momentum vector is horizontal and so there is no difference between the two types of tilt (Yeadon, 1993c). When twist is initiated during the contact phase there will be a component of angular momentum about the twist axis at takeoff and so the total angular momentum vector will not be horizontal (Yeadon, 1993b). For an axially symmetric rigid body in this situation, the visible tilt at takeoff will be zero whereas the mechanical tilt might be 5°. After half a somersault the mechanical tilt will still be 5° but the visible tilt will be 10° (Yeadon, 1993b) since the twist axis precesses about the angular momentum vector (Yeadon, 1993a). This poses something of a problem for 1½ somersaulting dives with a contact twist contribution. As with purely aerial twisting techniques, the mechanical tilt must be brought close to zero in order to stop the twist. If this is done then there will still be 5° of visible tilt remaining and the diver will enter the water tilted causing a sideways splash on entry. On the other hand if the visible tilt is brought close to zero there will be -5° of mechanical tilt and the diver may start to twist in the opposite direction on entry. These considerations suggest that too much contact contribution to the twist is likely to adversely affect the entry into the water and result in a dive with a poor score.

In any performance of a given movement there will be variability in execution (van Beers, Haggard & Wolpert, 2004) and so any theoretical optimisation should take such variability into account as in, for example, Hiley and Yeadon (2013). Studies using repeated trials to determine variability in elite performances of whole body movements have found coordination timing precision mean values of between 8 ms and 12 ms (Hiley, Zuevsky & Yeadon, 2013; Hiley & Yeadon, 2016a, 2016b). In any viable limiting movement there would need to be sufficient flexibility to accommodate timing variations of the order of 10 ms.

When investigating the limits of any twisting technique the number of twists that are possible will depend upon how much tilt can be produced since the twist rate increases with the tilt angle (Yeadon, 1993a; Mikl & Rye, 2016). The aim of the present research study is to determine the limits of contact and aerial techniques for producing twist in reverse 1½ somersault dives.

METHODS

An angle-driven computer simulation model of aerial movement (Yeadon, 1990a; Yeadon, Atha & Hales, 1990) was used to determine the limits of asymmetrical arm, hip and chest aerial techniques, with and without a contact contribution, for producing twist in a reverse 1½ somersault dive. The segmental inertia parameters of a male international springboard diver (height 1.79 m, mass 69.7 kg) used in the simulations were calculated from anthropometric measurements (Yeadon, 1990b). The model comprised 11 segments and required the initial angular momentum and body orientation as input together with the time histories of the joint angles. Since knee flexion was not used the model was effectively reduced to nine segments: upper trunk + head, lower trunk, pelvis, two legs and two upper and two lower arms. Side flexion and hyperextension were shared between the hips and the spine as described in Yeadon and Hiley (2018). The legs moved together reducing the six degrees of freedom at the hip joints and lower spine to two independent degrees of freedom. The shoulder centres were allowed to move within the upper trunk segment as a function of the angle between arm and upper trunk as in Begon, Wieber and Yeadon (2008).

The equations of motion for constant angular momentum (Yeadon, 1990c) were solved numerically for whole body angular velocity from which somersault, tilt and twist angles were obtained. Somersault gave the whole body rotation about the angular momentum vector, tilt gave the angle between the longitudinal axis and the plane perpendicular to the angular momentum vector, and twist gave the rotation about the longitudinal axis. The model has been evaluated by comparing the twist angles from simulation with those in performances of trampolining (Yeadon et al., 1990), springboard diving (Yeadon, 1993e), and tumbling (Yeadon & Kerwin, 1999).

The number of twists that can be achieved is limited by the time the body can be extended and so, in general, flight time and somersault momentum will be limiting factors. For dives from the three-metre springboard flight time has an upper limit of around 1.5 s and it is possible to perform a 2½ twisting reverse 2½ somersault which will have more angular momentum than a reverse 1½ somersault dive in the straight position. As a consequence, flight time was set at 1.5 s and no specific constraints were required to limit angular momentum.

The model was used to simulate the aerial phase of reverse 1½ somersaults in which twist was initiated during the first 0.75 s and was stopped during the following 0.75 s using asymmetrical movements of the arms, hips and chest to produce tilt and subsequently to remove it. The maximum amounts of twist in the first 0.75 s during which tilt is produced and in the last 0.75 s during which tilt is removed were added together to determine a limiting movement with the maximum whole number of twists. An optimised simulation was then found in which the target angles of somersault, tilt and twist were met. A contact tilt contribution of up to 10° was then introduced in each case and the optimisation process repeated to determine the limiting movement. Three cases of asymmetrical arm movement (with and without asymmetrical hips) and one of asymmetrical chest movement (with and without asymmetrical arm movement) were considered. One case of contact twist (with a symmetrical arm movement) was also investigated. Details are given in the following paragraphs.

Five constraints were imposed when producing an optimised simulation: (a) the final twist angle was an odd number of half revolutions, (b) the final somersault angle (trunk 25° short of vertical) was appropriate for hands, hips and feet to have the same water entry point for a three-metre springboard dive, (c) the shoulder and hip angles at entry (140° and 155°) were fixed at values consistent with (b), (d) the angle of pike (between upper trunk and legs) after the twisting phase (in which the body was straight) lay between 70° and 120°, (e) the final (mechanical) tilt angle was zero, (f) the time of flight was 1.5 s.

Each change in joint angle was specified by the start and end angle values and the start and end times and was effected using a quintic function with zero velocity and acceleration at the endpoints (Hiley & Yeadon, 2003). Lower limits on the duration of arm and hip movements were based on times between angle turning points in recorded performances of twisting double somersaults on trampoline as in Yeadon and Hiley (2017). For arm abduction through 180° a minimum duration of 0.30 s was imposed while 0.20 s was used for a 90° arm movement. For 90° hip flexion / extension a lower limit of 0.25 s was set and 0.20 s was used for a change from 40° hip and spine hyperextension to 40° side flexion (a change in hula angle of 90°). A lower limit of 0.20 s was imposed on a 90° torsion of the upper trunk relative to the lower trunk and pelvis segment (chest asymmetry). The corresponding maximum angular velocities were 19.6 s^{-1} (arm), 11.8 s^{-1} (hip), 14.7 s^{-1} (hula) and 14.7 s^{-1} (chest).

In the first case of asymmetrical arm movement (Case 1), the left arm was lowered sideways (adduction) through 180° while the body moved from 40° back hyperextension to 40° side flexion to the left. Subsequently the right arm was lowered down the front (shoulder extension) through 180°after around a quarter twist had occurred and the hips were extended (Figure 1a). The arms remained in this configuration with an extended body while the majority of the twist occurred and then the left arm was raised laterally through 180° at around a half twist short of the target angle (while the hips flexed again) followed later by the right arm in order to remove the tilt and stop the twist. Finally the arms were lowered to give an angle of 140° between arms and trunk and the hips were extended to give an angle of 155° between legs and pelvis in preparation for entry.

In the second case of asymmetrical arm movement (Case 2), the right arm was raised laterally through 90° while the left arm was lowered laterally through 90° and the body moved from hyperextension to side flexion. The right arm was subsequently adducted from overhead to the side of the body when the twist angle approached a half twist in order to increase the tilt angle further (Figure 1b). The arms remained adducted with an extended body while the twist occurred and subsequently the left arm was abducted followed by the right arm (while the hips flexed) to remove the tilt and stop the twist. The arm and hip angles were then adjusted to their final positions as in the first case.

In the third case, the right arm was raised laterally through 90° while the left arm was lowered laterally through 90° and the body moved from hyperextension to side flexion. Subsequently each arm moved through 180° laterally as the twist angle approached a half twist in order to increase the tilt angle further (Figure 1c). The arms then remained straight during the twist or were flexed as in Figure 1c. Subsequently the hips flexed and each arm moved through 180° simultaneously to remove the tilt as the twist neared completion and finally the left arm was raised parallel to the sagittal plane and the entry configuration was adopted.

In the case of asymmetrical chest movement (Case 4), the upper trunk was twisted to the left through 90° relative to the lower trunk and pelvis. Subsequently the left arm was raised laterally through 90° and the right arm was lowered laterally through 90° as the upper trunk untwisted (Figure 2a). This configuration was maintained during the twist and then each arm moved through 180° laterally while the hips flexed and finally the left arm was raised in preparation for entry. A variant was also explored in which the arms were abducted symmetrically after the initial chest torsion and tilt was removed using asymmetrical arms as in cases 1 and 2.

In the contact twist movement with symmetrical arms (Case 5), the arms remained overhead initially and were then lowered parallel to the sagittal plane at around the quarter twist position (Figure 2b). The arms remained adducted while the twist occurred and subsequently the left arm was abducted followed by the right arm (while the hips flexed) to remove the tilt and stop the twist. The arm and hip angles were then adjusted to their final positions.

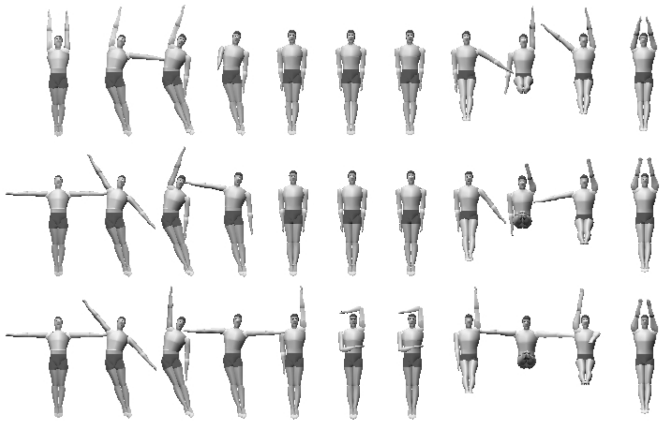

Figure 1. Asymmetrical arm and hip movements used to produce tilt in a reverse 1½ somersault dive: (a) 180° of movement of each arm (upper sequence), (b) 360° total arm movement (middle sequence), (c) 270° of movement of each arm (lower sequence). Asymmetrical arm movement was used to remove the tilt in each case.

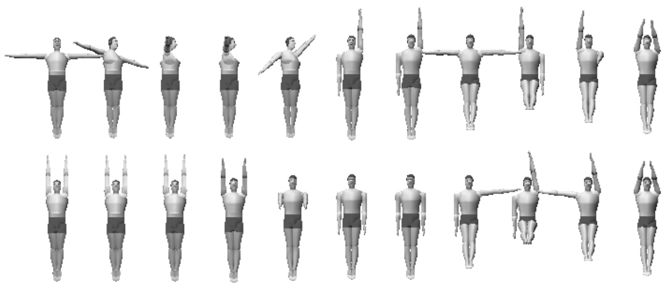

Figure 2. (a) Asymmetrical movement of the chest and arms to produce aerial twist (upper sequence) and (b) symmetrical movement of the arms in conjunction with contact twist (lower sequence). Asymmetrical arm movement was used to remove the tilt in each case.

The procedure used for finding the limiting movement in each of the three cases of asymmetrical arm and hip movement was the same as in Yeadon & Hiley (2018). Initially simulated annealing (Goffe, Ferrier & Rogers, 1994) was used to vary between four and 11 parameters (comprising up to one arm angle and up to 10 start times and durations of hip and arm movement) to produce tilt and maximise twist after 0.75 s (using between 26,000 and 81,000 simulations). Secondly the ability of asymmetrical arm movement to remove tilt and stop the twist was assessed by running optimisations of time-reversed simulations that started with the end of flight conditions at time 1.5 s in which tilt was produced by asymmetrical arm movements (one hip flexion angle and up to five arm and hip timing parameters with between 33,000 and 44,000 simulations), using maximum twist at 0.75 s as the optimisation criterion. The amount of twist at 0.75 s in the first optimisation was added to the twist in the reverse simulation at 0.75 s in the second optimisation to provide an estimate of the maximum twist possible. The maximum twist value was rounded down to the nearest number of whole twists.

Simulated annealing was then used to find a complete simulated dive in which the above twist value was achieved at 1.5 s along with zero tilt and the required somersault using a score function that penalised deviations from the final target orientation angles. A solution was deemed to have been found when each of the somersault, tilt and twist angles was within 1° of the target value. Additional optimisations were run to seek solutions with the arms less adducted during the twisting phase. Subsequently optimisations were run in which contact twist was allowed to introduce up to 10° tilt in order to increase the range of arm abduction in successful simulations. The same procedures were used to find the limiting dives for asymmetrical chest movement (Case 4) and the symmetrical arm movement with contact twist (Case 5).

RESULTS

For the first case of arm asymmetry (Case 1) in which each arm moved through 180° (Figure 1a) up to 16° of tilt could be produced, resulting in a limiting dive with 2½ twists that allowed for a range of 9° arm abduction (Table 1). The tilt was removed using abduction of the right arm and then the left arm through 180° while piking (Figure 1a). When asymmetrical hips were introduced the limiting twist increased to 3½ revolutions (Figure 3) with an arm abduction range of 3°. Introducing up to 5° of contact tilt contribution allowed the arm abduction range to be increased to 8° (Table 1). Allowing the elbows to be flexed during the twisting phase (with body extended) increased the arm abduction range to 10°.

Table 1. Maximum twist for asymmetrical aerial and symmetrical contact techniques

	asymmetry						
	arms	**hips**	**chest**	**contact tilt**	**max tilt**	**twist [rev]**	**arm range**
Case 1	**360°**	**--**	**--**	**--**	**16°**	**2.5**	**9°**
	360°	**90°**	**--**	**--**	**16°**	**3.5**	**3°**
	360°	**90°**	**--**	**5°**	**16°**	**3.5**	**8°**
Case 2	**360°**	**--**	**--**	**--**	**16°**	**2.5**	**18°**
	360°	**90°**	**--**	**--**	**18°**	**3.5**	**6°**
	360°	**90°**	**--**	**10°**	**26°**	**4.5**	**10°**
Case 3	**540°**	**--**	**--**	**--**	**23°**	**4.5**	**9°**
	540°	**90°**	**--**	**--**	**27°**	**5.5**	**7°**
	540°	**90°**	**--**	**10°**	**30°**	**5.5**	**9°**
Case 4	**--**	**--**	**90°**	**--**	**13°**	**1.5**	**33°**
	180°	**--**	**90°**	**--**	**16°**	**3.5**	**1°**
	180°	**--**	**90°**	**10°**	**26°**	**5.5**	**5°**
Case 5	**360°**	**--**	**--**	**10°**	**18°**	**3.5**	**16°**

Note: The arms are straight throughout the above simulations

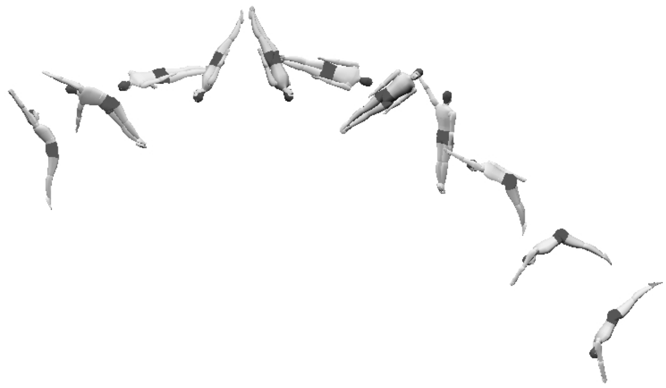

Figure 3. Asymmetrical movement of each arm through 180° combined with asymmetrical hip movement can produce up to 3½ twists in a reverse 1½ somersault dive (side view).

For the second case of arm asymmetry (Case 2) in which the left arm was abducted through 90° and the right arm moved through 270° (Figure 1b), up to 16° of tilt could be produced, resulting in a limiting dive with 2½ twists that allowed for a range of 18° arm abduction (Table 1). The tilt was removed using sequential abduction of the right and left arms as in Case 1. When asymmetrical hips were introduced the maximum tilt increased to 18° and the limiting twist increased to 3½ revolutions with an arm abduction range of 6°. Introducing 10° of contact tilt resulted in a maximum tilt angle of 26° with 4½ twists (Figure 4) and an arm abduction range of 10° (Table 1). Allowing the elbows to be flexed during the twisting phase increased the arm abduction range to 13°.

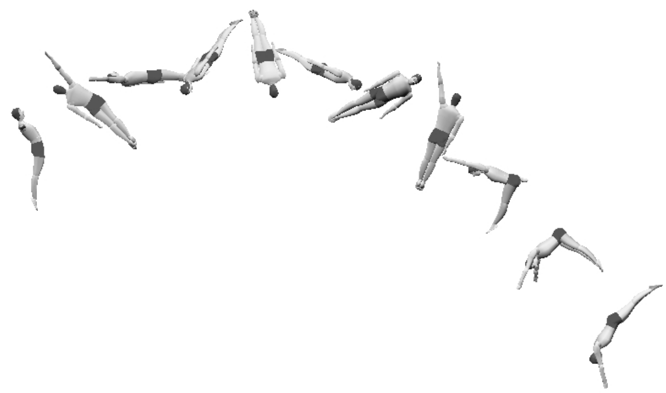

Figure 4. Asymmetrical arm movement through a total of 360° can produce up to 4½ twists in a reverse 1½ somersault dive (side view).

For the third case of arm asymmetry (Case 3) in which both arms moved through 270° (Figure 1c), up to 23° of tilt could be produced, resulting in a limiting dive with 4½ twists that allowed for a range of 9° arm abduction (Table 1). The tilt was removed using 180° of lateral movement of each arm while piking (Figure 1c). When asymmetrical hips were introduced the maximum tilt increased to 27° and the limiting twist increased to 5½ revolutions with an arm abduction range of 7° (Table 1). Allowing the elbows to be flexed during the twisting phase (Figures 5, 6) increased the arm abduction range to 11°. During the twisting phase the tilt angle, the twist rate and the somersault rate were all approximately constant (Figure 6). Introducing 5° of contact tilt allowed the arm abduction range to be increased further to 16°. This was greater than the 9° range that could be achieved using straight arms (Table 1).

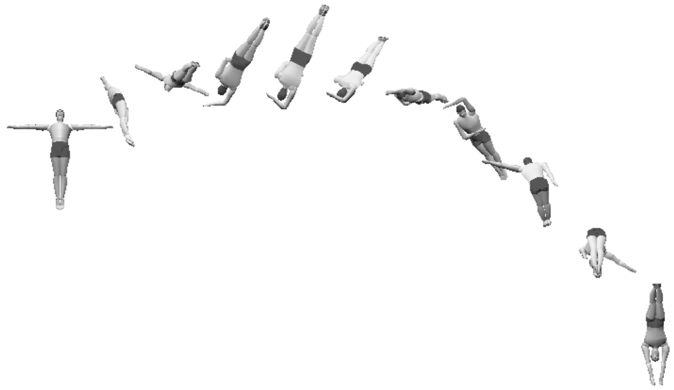

Figure 5. Asymmetrical movement of each arm through 270° combined with asymmetrical hip movement can produce up to 5½ twists in a reverse 1½ somersault dive (front view).

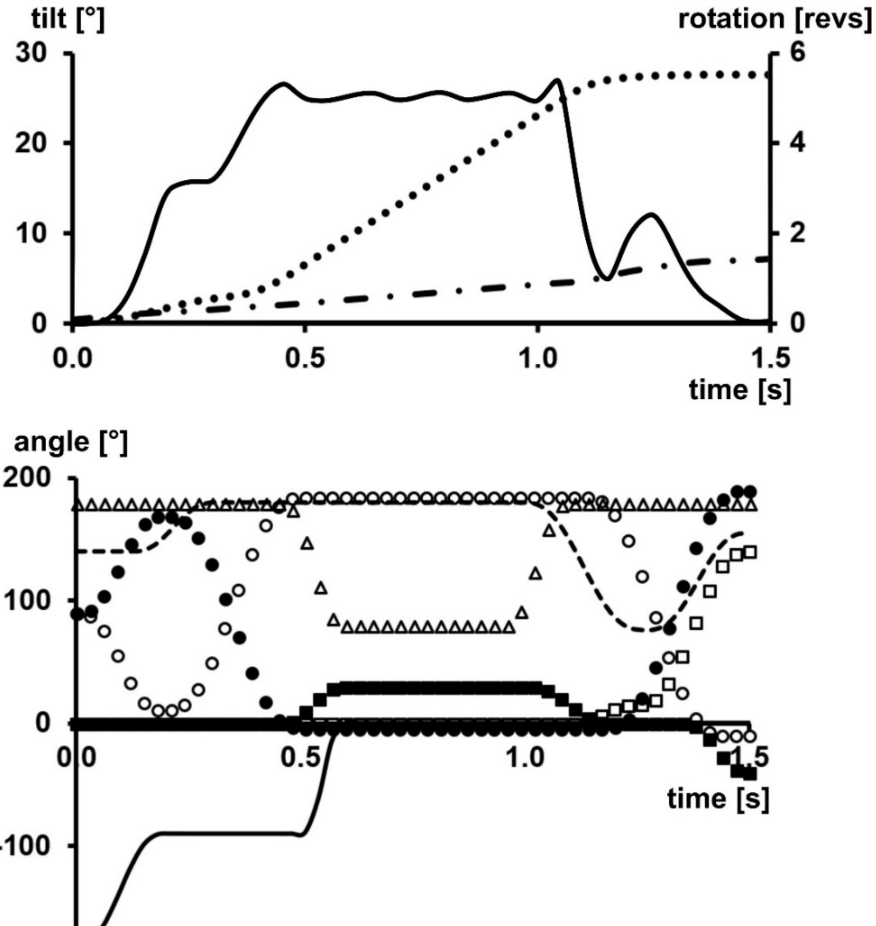

Figure 6. Somersault in revolutions (dashed line), tilt in degrees (solid line) and twist in revolutions (closed circles) during the reverse 1½ somersault dive with 5½ twists produced by asymmetrical arm movement through 540° and asymmetrical hip movement through 90° (upper graph); hula angle of the hip (solid line), hip flexion (dashed line), left arm abduction (open circles), right arm abduction (closed circles), left arm elevation (open square), and right arm elevation (closed squares), left and right elbow angle (open triangles) in degrees (lower graph).

In Case 4 where the upper trunk was twisted through 90° to the left relative to the pelvis and the arms were adducted simultaneously as the upper trunk untwisted, up to 13° of tilt could be produced, resulting in a limiting dive with 1½ twists that allowed for a range of 33° arm abduction (Table 1). When the arms were allowed to move asymmetrically (Figure 2a), up to 16° of tilt could be produced, resulting in a limiting dive with 3½ twists that allowed for a range of 1° arm abduction (Table 1). Introducing 10° of contact tilt resulted in a maximum tilt angle of 26° with 5½ twists and an arm abduction range of 5° (Table 1). Allowing the elbows to be flexed during the twisting phase increased the arm abduction range to 8° (Figure 7).

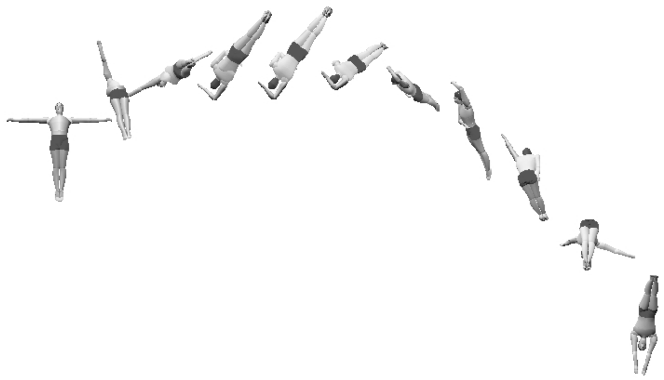

Figure 7. Asymmetrical chest torsion through 90° and asymmetrical movement of each arm through 90° can produce up to 5½ twists in a reverse 1½ somersault dive (front view).

In Case 5 where contact twist was used in conjunction with a symmetrical lowering of the arms (Figure 2b), 18° of tilt was produced, resulting in 3½ twists (Figure 8) and an arm abduction range of 16° (Table 1). Allowing the elbows to be flexed during the twisting phase increased the arm abduction range to 23°.

Figure 8. Symmetrical movement of each arm through 180° arms in conjunction with contact twist can produce up to 3½ twists in a reverse 1½ somersault dive (front view).

DISCUSSION

The aim of the present research study was to determine the limits of contact and aerial techniques for producing twist in reverse 1½ somersault dives. It was found that aerial techniques comprising asymmetrical arm and hip movements were capable of producing between 2½ and 5½ twists, asymmetrical chest torsion up to 5½ twists when used in combination with contact twist, and symmetrical arm movement in conjunction with contact twist up to 3½ twists. For each of the five limiting dives there were nearby solutions with ranges of arm abduction in the twisting phase from 8° to 23°. The use of flexed elbows rather than straight arms during the twisting phase gave increases in the arm abduction range from 1° to 10°. The reverse 1½ with 5½ twists has not yet been attempted in competition and has not been assigned a degree of difficulty. The current maximum number of twists in a reverse 1½ somersault twisting dive performed in competition from the three metre springboard is 4½ twists (FINA, 2017, Appendix 2).

The coordination of the arm movement timing with the twist angle is crucial for the production of tilt which results in the twist. After the initial lowering of the left arm for a twist to the left (Yeadon, 1993c) the right arm may be lowered down the front at around the quarter twist position (Case1: Figures 1a, 3) or down the side at around the half twist position (Case 2: Figures 1b, 4) or in Case 3 after the initial 90° abduction / adduction of the arms, the arms reverse positions at around a half twist (Figures 1c, 5). Over the three cases the increasing amounts of asymmetrical arm movement result in greater amounts of tilt and an increased number of twists (Table 1).

Configuration changes for removing the tilt are also coordinated with the twist angle. In cases 1 and 2 the arms are abducted successively at around the start and end of the last half twist (Figures 1ab, 3,4). In Case 3 both arms are moved simultaneously through 180° to remove the tilt as the hips are flexed (Figures 1c, 5). The hip flexion changes the whole body motion from the rod mode into the disc mode (Yeadon, 1993a). In the rod mode the twist angle increases monotonically and the tilt angle remains relatively constant whereas in the disc mode the twist angle and tilt angle both oscillate. This oscillation of the tilt angle assists in reducing the tilt to zero (Yeadon, 1993b) which might explain why repiking in a twisting dive prior to entry is a universal trait of elite performance.

The introduction of 10° contact tilt results in tilt increases of 8°, 3° and 10° (Table 1: Cases 2, 3, 4) with resulting additional twist of 1, 0 and 2 revolutions. In the first four cases contact twist makes a much smaller contribution to the total tilt compared to aerial techniques in line with the majority of performances in Yeadon (1993e). When contact twist is used the tilt away from the vertical on entry is visible (Figures 7, 8).

It is evident that the use of contact twist with symmetrical configurational changes has only limited capability for producing a maximal twist dive (Case 5, Table 1) whereas asymmetrical arm and hip movement has much greater capability (Case 3, Table 1) even when not supplemented by contact twist. The use of flexed elbows during the twisting phase (Figures 5, 7) rather than straight arms (Figures 1, 2) is beneficial and can add up to 10° to the arm abduction range for a given dive. This result underpins the universal adoption of flexed arms in twisting dives. The use of contact twist in addition to aerial twist can increase the number of twists (Table 1) but this is at the expense of a tilted entry (Figures 7, 8).

In any performance of a given dive there will be variability in execution which may be compensated for later in flight by making adjustments in configuration using feedback control (Yeadon & Hiley, 2014). In each of the five limiting dives there was some margin to allow compensation for variation in execution as indicated by the amounts of additional arm abduction available in the twisting phase (ranging from 8°

to 23°). In order to assess how much margin for compensation might be needed the start times and durations of joint angle changes, in the production of tilt and twist for the third case of arm asymmetry in which 5½ twists were produced, were each perturbed by 0.01 s (Hiley et al., 2013; Hiley & Yeadon, 2016a, 2016b) to determine the effect on somersault and twist. In the perturbed simulations there was a range of 7% in twist at 0.75 s and 1% in somersault. The arm abduction range of 11° corresponded to a range of 10% in twist which would accommodate the 7% arising from timing variations. A similar result was obtained for the case of chest torsion (Case 4) which also produced 5½ twists. These results indicate that these two limiting movements are realistic possibilities. In addition it can be inferred that the coordination precision cannot be much worse than 10 ms since otherwise the arm abduction range would not be sufficiently large to allow compensatory adjustments.

The effects of a 10% reduction in all lower bounds of arm and hip movement durations on optimisations were assessed. The maximum tilt increased by less than 1° in all cases. The arm abduction range for the two limiting dives with 5½ twists (Case 3 and Case 4) increased by 5° and 1° but the limiting dives did not change. Although such timing changes may make the limiting dives easier, their effects are constrained by the relationship between somersault rate, tilt angle and twist rate (Yeadon, 1993a; Mikl & Rye, 2016). The above considerations also imply that increasing the time of flight from 1.5 s to 1.65 s would not change the limiting dives. The results for limiting dives from the 10-metre platform will be the same since the flight time is slightly higher than from three-metre springboard although the required configuration at entry will be different due to the higher vertical entry speed.

The segmental inertia parameters of an elite male diver were used in the determination of the limiting movements. The ratio of transverse moment of inertia to longitudinal moment of inertia was 16.0 with arms adducted to the side and 20.3 with one arm overhead. For a given tilt angle this ratio governs the number of twists per somersault in the twisting phase (Yeadon, 1993a; Mikl & Rye, 2016) and so the advantage of having one arm overhead is clear. For comparison the inertia parameters of two other male competitive springboard divers (ratios: 16.5, 20.2; 19.1, 22.8) were used to determine the limiting dive for asymmetrical arm movement (Case 3). It was found that the same limiting dive was obtained again for both divers with arm adduction ranges in the twisting phase of 11° and 18° compared with the 11° (elbows flexed) of the original diver. A particular individual athlete's segmental inertias may result in the limiting movements having less twist (Mikl, 2016). The same may also be true of a particular individual's strength and precision limits. The aim of this study, however, was to determine the limits for elite divers.

It can be concluded that in a reverse 1½ somersault dive, asymmetrical arm and hip movement during flight can produce 5½ twists, even without any contact contribution. Asymmetrical chest and arm movement supplemented by contact twist can also produce 5½ twists although the effect of contact twist will be apparent at entry. To accomplish these limiting dives the timing of configurational changes needs to be coordinated with the progress of the twist with a precision of 10 ms or better.

CONFLICT OF INTEREST STATEMENT

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

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