Human Movement Science 58, 97-107, 2018

# The limits of aerial techniques for producing twist in forward 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 forward 1½ somersault dive from a three-metre springboard using various aerial 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 whole number of 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 two to five twists with arm abduction ranges lying between 6$^{o}$ and 17$^{o}$. Similar results were obtained when the inertia parameters of two other springboard divers were used.

Keywords: computer simulation, aerial movement, diving, twisting

## INTRODUCTION

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). Historically this rule lead to controversy as to whether it was possible to twist in flight without starting the twist during the board contact phase. While it was accepted that aerial twist could be produced by counter-rotation of the hips (Eaves, 1969; Rackham, 1960), there was a problem in that a cycle of counter-rotation could produce a half twist but the method could not account for the continuous twisting that was seen in diving. Commenting upon the descriptions of twisting dives given by Barrow (1959a, 1959b), Orner (1959) stated that when twist is not taken from the diving board it can only be produced by counter-rotation and that “any postulated technique, in which the diver leaves the board without angular momentum about the desired axis of rotation and then has him 'Spinning', is faulty”. Barrow (1959c) replied to Orner and showed how the total angular momentum could be resolved about tilted body axes. This was insufficient for Eaves (1960) who observed: “Mr. Barrow offers no mechanism whereby the body is tilted... and the only feasible mechanism is a series of rapid rotations of the arms across the front of the body in the opposite direction to the tilt. It can be shown that this cannot be done quickly enough to be effective... “. Rackham (1958) also held the same view but reversed his position after experiments in which divers produced such a twist (Rackham, 1970) and agreed with Travis (1968) that asymmetrical arm movements could product twist in a somersault. Frolich (1979) and Pike (1980) subsequently showed that it is theoretically possible to convert a plain somersault into a twisting somersault by tilting the twist axis out of the vertical somersault plane by means of asymmetrical arm movements. Frolich (1980) observed that in addition to arm movements any relative movement of body segments that produces tilt will result in twist. Rackham

(1970) and Batterman (1974) proposed a torsion of the upper body in the direction of twist when in the piked position, causing the legs to swing in the opposite direction so that when the body extends it will be tilted.

Yeadon (1993a, b, c, d) used a rigid body model of aerial movement together with an 11-segment computer simulation model to investigate contact and aerial twisting techniques by considering contributions to the tilt angle. 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). While dives that rotate backwards typically show an early twist, indicating the presence of contact twist, forward somersaulting dives often exhibit no twist until well after takeoff. The question arises as to the twist limits of aerial twisting techniques. Since the twist rate increases with the tilt angle (Yeadon, 1993a; Mikl & Rye, 2016), the twist limits will depend upon how much tilt can be produced.

Yeadon (2013) used computer simulation to investigate the capabilities of various aerial twisting techniques for producing twist in triple somersaults in the aerials event of freestyle skiing. It was concluded that six twists should be possible. Yeadon and Hiley (2017) found that three twists is the limit for twist in the second somersault of a straight backward double somersault on trampoline and that 3½ twists is the limit for twist in the second somersault of a piked forward double somersault. The aim of the present research study is to determine the limits of aerial twisting techniques comprising asymmetrical movements of arms, hips and chest in forward rotating 1½ somersault dives with twist.

## METHODS

An angle-driven computer simulation model of aerial movement (Yeadon, 1990a; Yeadon et al., 1990) was used to determine the limits of asymmetrical arm, hip and chest techniques for producing aerial twist in a forward 1½ somersault dive. The segmental inertia parameters of a male international springboard diver (height 1.79 m, mass 69.7 kg) were calculated from anthropometric measurements (Yeadon, 1990b) and were used in the simulations. 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. For the majority of simulations elbow and knee flexion were not used. As a consequence the model was effectively reduced to seven segments: upper trunk + head, lower trunk, pelvis, two legs and two arms. Side flexion was shared between the hips and the spine as was hyperextension whereas forward flexion occurred solely at the hip joints for the first $90^{o}$ of flexion and thereafter was shared between the hips and spine (Yeadon, 1990c). In addition the two legs moved together so that the six degrees of freedom at the hip joints and lower spine became two independent degrees of freedom. The model was modified so that the locations of the shoulder centres within the upper trunk segment were a function of the angle between arm and upper trunk as in Begon et al. (2008).

Constant angular momentum during flight was assumed and the equations of motion were solved numerically for whole body angular velocity from which somersault, tilt and twist angles were obtained by numerical integration. Somersault gave the whole body rotation about the (horizontal) angular momentum vector, tilt gave the angle between the longitudinal axis and the vertical 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), freestyle skiing (Yeadon, 1989), rings dismounts (Yeadon, 1994), high bar dismounts (Yeadon, 1997), and tumbling (Yeadon & Kerwin, 1999).

In multiple somersaults with multiple twists, the number of twists that can be achieved is limited by the time that 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 triple twisting forward 2½ somersault which will have more angular momentum than a forward 1½ somersault dive in the straight position. As a consequence flight time was set at 1.5 s in this study and no specific constraints were needed to limit angular momentum.

The model was used to simulate the aerial phase of forward 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. Four cases of asymmetrical arm movement were considered and one case for each of asymmetrical hip and asymmetrical chest movement. Details are given in the following paragraphs.

Five constraints were imposed when producing an optimised simulation: (a) the final twist angle was a whole number of revolutions, (b) the final somersault angle (trunk 25$^o$ 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 (150$^o$ and 155$^o$) were fixed at values consistent with (b), (d) the final tilt angle was zero, (e) 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 & Hiley (2017). For arm abduction through 180$^o$ a minimum duration of 0.30 s was imposed while 0.20 s was used for a 90$^o$ arm movement. For 90$^o$ hip flexion / extension a lower limit of 0.25 s was set and 0.20 s was used for a change from hip flexion to 60$^o$ side flexion (a change in hula angle of 90$^o$). A lower limit of 0.20 s was imposed on a 90$^o$ 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, the left arm was raised sideways through 90$^o$ while the right arm was lowered through 90$^o$ (Figure 1a). The arms remained in this configuration with an extended body while the twist occurred and then the arm movement was reversed (while the hips flexed again) to remove the tilt and stop the twist. Finally the arms were raised to give an angle of 150$^o$ between arms and trunk and the hips were extended to give an angle of 155$^o$ between legs and pelvis in preparation for entry.

In the second case the right arm was adducted from overhead to the side of the body followed by the left arm 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 of asymmetrical arm movement, the left arm was first lowered parallel to the sagittal plane and then both arms moved through 180$^{o}$ in the frontal plane as the hips extended (Figure 2a). At this point the arms either remained straight or were flexed as in Figure 2a during the twisting phase. Finally the arm movement was reversed and then the left arm was raised parallel to the sagittal plane and the entry configuration was adopted.

The fourth case started with a lowering of the left arm followed by adduction / abduction of both arms with hips extending as in the third case (Figure 2b). After a half twist the right arm was abducted to an overhead position to join the left arm for the twisting phase. Finally the right arm was first lowered laterally and then both arms were adducted / abducted to remove the tilt prior to adopting the entry configuration as in the third case.

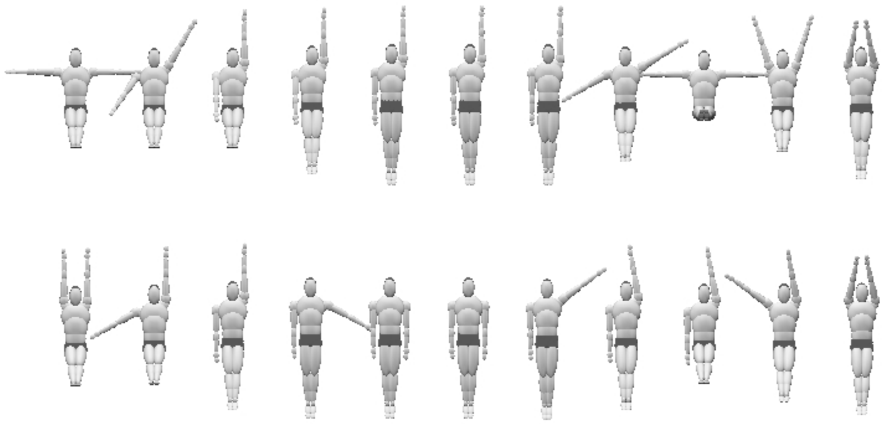

Figure 1. Asymmetrical arm movements used to produce and remove tilt in a forward 1½ somersault dive: (a) 90$^{o}$ of movement of each arm (upper sequence), (b) 180$^{o}$ of movement of each arm movement (lower sequence).

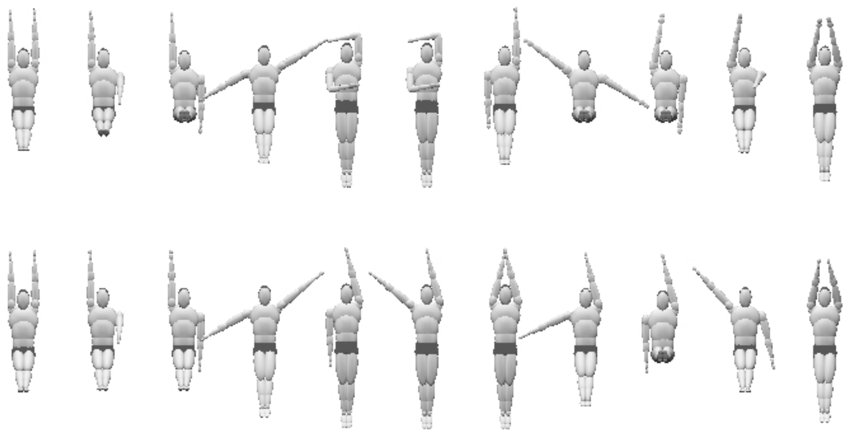

Figure 2. Asymmetrical arm movements used to produce and remove tilt in a forward 1½ somersault dive: (a) 360$^{o}$ of tilt producing arm movement (upper sequence), (b) 540$^{o}$ of tilt producing arm movement (lower sequence).

The procedure used for finding the limiting movement in each of the four cases of asymmetrical arm movement was the same. Firstly simulated annealing (Goffe et al., 1994) was used to vary between four and ten parameters (comprising up to three angles and up to seven start times and durations of hip flexion / extension and arm adduction / abduction) for the production of tilt and twist (using between 27,000 and 78,000 simulations). Since there would be some trade-off between maximising tilt and maximising twist depending on the duration used for tilt production, the optimisation criterion for the production of tilt and twist was chosen to be that of maximising twist after 0.75 s. Secondly the ability of asymmetrical arm movement to remove tilt and stop the twist was assessed by running optimisations of reverse simulations that started with the end of flight conditions at time 1.5 s in which tilt was produced by asymmetrical arm movements (up to two hip flexion angles and up to nine arm and hip timing parameters with between 35,000 and 81,000 simulations) within the permitted ranges, using maximum twist at 0.75 s as the optimisation criterion. The angular momentum value was adjusted iteratively so that the somersault rotation values in the two optimisations coincided at the same point in time. The amount of tilt allowed to be produced was restricted to the smaller value of the two optimisations. 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 from 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 $1^{o}$ of their target values. Depending on the complexity of the arm movement, between 13 and 21 parameters (using between 56,000 and 114,000 simulations) were used to vary the hip flexion and the asymmetrical arm movements which produced and removed tilt along with a parameter to adjust the angular momentum value. Additional optimisations were then run to seek solutions with the arms less adducted during the twisting phase.

The same procedure was used to find the limiting dives for asymmetrical hip movement and asymmetrical chest movement. In the case of asymmetrical hip movement the hips moved from $60^{o}$ forward flexion to $60^{o}$ side flexion while the arms were held abducted at $90^{o}$ (Figure 3a). The arms were then adducted to the body symmetrically and the configuration held during the twisting phase. Subsequently the left arm was abducted followed by the right arm (as the hips extended) to remove the tilt prior to adopting the entry configuration since asymmetrical hip movement was incapable of removing that amount of tilt.

In the case of asymmetrical chest movement the upper trunk was turned $90^{o}$ to the left with arms wide while the hips continued to flex from a hip angle of $120^{o}$ to a hip angle of $90^{o}$ (Figure 3b). The arms were then raised laterally overhead while the hips extended and the trunk untwisted; this configuration was maintained during the twisting phase. Subsequently the right arm was lowered laterally followed by the left arm as the hips flexed. The right arm was then raised laterally while the left arm was raised parallel to the sagittal plane with the hips extending into the entry configuration.

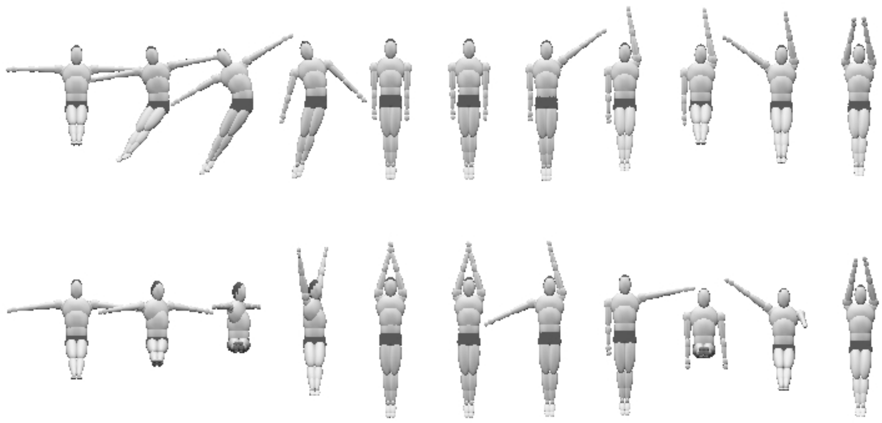

Figure 3. Asymmetrical movements of the hips (a: upper sequence) and chest (b: lower sequence) used to produce tilt. Asymmetrical arm movement was used to remove the tilt in each case.

## RESULTS

For the first case of arm asymmetry (case 1) in which each arm moved through $90^o$ (Figure 1a), $9.0^o$ of tilt was produced when twist was maximised (1.38 rev) in the first 0.75 s. In the last 0.75 s of the simulated dive, up to $13.3^o$ of tilt could be removed and when this was restricted to $9.0^o$, the maximum twist was 1.22 rev in the second half of the dive. The sum of these two twist amounts (2.60 rev) indicated that two twists should be possible with some margin (0.60 rev) to spare (Table 1). Simulated annealing found such a limiting dive (Figure 4) and other solutions with an arm abduction range of $17^o$ in the twisting phase (Table 1).

Table 1. Maximum twist in tilt production phase and tilt removal phase

| | max tilt [deg] | twist in first 0.75s [rev] | twist in last 0.75s [rev] | max twist [rev] | twist margin [rev] | arm abduction range [deg] | angular momentum [ss/s] |
|---|---|---|---|---|---|---|---|
| arms case 1 | $9.0^o$ | 1.38 | 1.22 | 2.0 | 0.60 | $17^o$ | 0.96 |
| arms case 2 | $15.2^o$ | 1.48 | 1.28 | 2.0 | 0.76 | $18^o$ | 0.94 |
| arms case 3 | $19.9^o$ | 2.35 | 2.16 | 4.0 | 0.51 | $10^o$ | 0.90 |
| arms case 4 | $24.2^o$ | 2.75 | 2.69 | 5.0 | 0.44 | $7^o$ | 0.96 |
| hips | $18.8^o$ | 2.02 | 1.36 | 3.0 | 0.38 | $6^o$ | 0.89 |
| chest | $24.2^o$ | 3.12 | 2.59 | 5.0 | 0.71 | $15^o$ | 0.90 |

Note: twist margin is the difference between the sum of the twists in the two phases and the maximum twist in the limiting dive; angular momentum is in straight somersaults per second

Figure 4. Asymmetrical movement of each arm through 90$^o$ can produce up to two twists in a forward 1½ somersault dive (front view).

For the second case of arm asymmetry (case 2) in which the total arm asymmetrical movement was 360$^o$ (Figure 1b), 15.2$^o$ of tilt was produced when twist was maximised (1.48 rev) in the first 0.75 s. In the last 0.75 s up to 17.4$^o$ of tilt could be removed and when this was restricted to 15.2$^o$, the maximum twist was 1.28 rev in the second half of the dive. The sum of these two twist amounts (2.76 rev) indicated that two twists should be possible with some margin (0.76 rev) to spare (Table 1). Simulated annealing found such a limiting dive (Figure 5) and other solutions with an arm abduction range of 18$^o$ in the twisting phase (Table 1).

Figure 5. Asymmetrical movement of each arm through 180$^o$ can produce up to two twists in a forward 1½ somersault dive (front view).

For the third case of arm asymmetry in which the left arm was first lowered parallel to the sagittal plane and then each arm was moved through 180$^o$ (Figure 2a), 20.5$^o$ of tilt was produced when twist was maximised in the first 0.75 s. In the last

0.75 s up to 19.9° of tilt could be removed with 2.16 twists occurring in the second half of the dive. When the tilt angle was restricted to 19.9° in the first 0.75 s, 2.35 twists could be produced. The sum of these two twist amounts (4.51 rev) indicated that four twists should be possible with some margin (0.51 rev) to spare (Table 1). Simulated annealing found such a limiting dive and other solutions with an arm abduction range of 10° in the twisting phase (Table 1). When the arms were allowed to flex at the elbows during the twisting phase a similar limiting dive with four twists was found (Figure 6) with a greater margin of arm abduction range (16°).

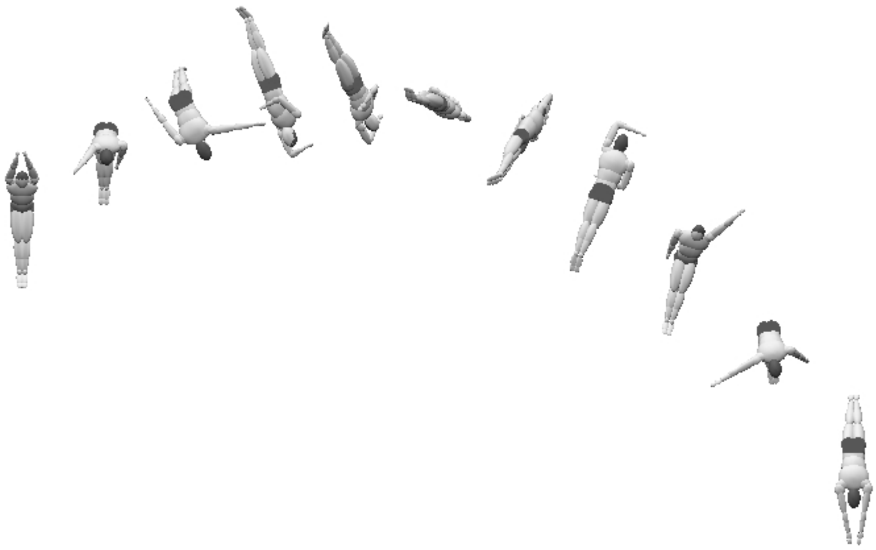

Figure 6. Asymmetrical movement of each arm through 180° can produce up to four twists in a forward 1½ somersault dive (front view).

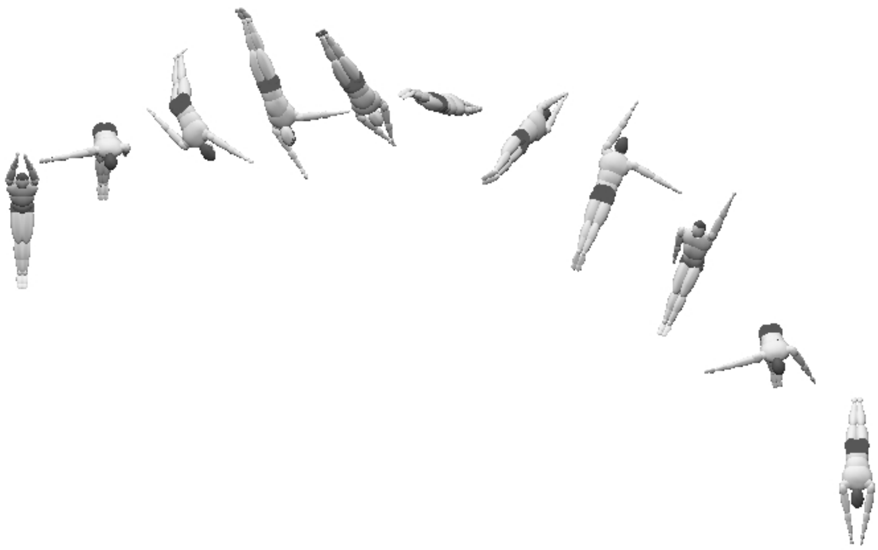

Figure 7. 540° of asymmetrical arm movement can produce up to five twists in a forward 1½ somersault dive (front view).

For the fourth case of arm asymmetry in which the arms started the same as case 3 but with the right arm being abducted overhead to give a twisting phase configuration with both arms overhead after 540$^{o}$ of tilt producing lateral arm movement (Figure 2b), 24.2$^{o}$ of tilt was produced with 2.75 twists in the first 0.75 s. In the last 0.75 s up to 27.1$^{o}$ of tilt could be removed and when this was restricted to 24.2$^{o}$, 2.69 twists were obtained in the second half of the dive. The sum of the two twists (5.44 rev) indicated that five twists should be possible with some margin (0.44 rev) to spare (Table 1). Simulated annealing found such a limiting dive (Figure 7) and other solutions with an arm abduction range of 7$^{o}$ in the twisting phase (Table 1).

For the case of hip asymmetry in which the body moved from a forward flexed position into side flexion with wide arms before straightening (Figure 3a), 19.5$^{o}$ of tilt was produced when twist was maximised in the first 0.75 s. In the last 0.75 s hip asymmetry could remove only 6.3$^{o}$ tilt and therefore asymmetrical arm movement (similar to case 2, Figure 1b) was used, allowing up to 18.8$^{o}$ of tilt to be removed with 1.36 twists occurring in the second half of the dive. When the tilt angle was restricted to 18.8$^{o}$ in the first 0.75 s, 2.02 twists were produced. The sum of the two twists (3.38 rev) indicated that three twists should be possible with some margin (0.38 rev) to spare (Table 1). Simulated annealing found such a limiting dive (Figure 8) and other solutions with an arm abduction range of 6$^{o}$ in the twisting phase (Table 1).

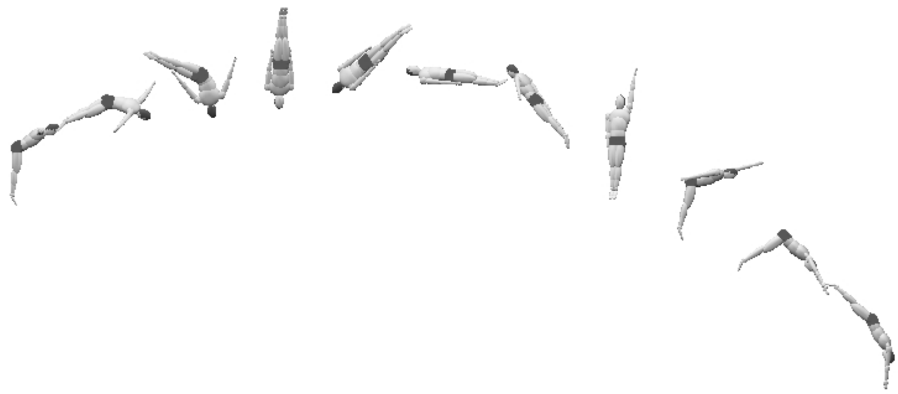

Figure 8. Asymmetrical hip movement can produce up to three twists in a forward 1½ somersault dive (side view).

For the case of chest asymmetry in which the upper trunk turned (with wide arms) through 90$^{o}$ to the left relative to the lower trunk and pelvis before straightening (Figure 3b), 24.2$^{o}$ of tilt was produced when twist was maximised with 3.12 twists in the first 0.75 s. In the last 0.75 s chest asymmetry could remove only 13.2$^{o}$ of tilt and consequently asymmetrical arm movement (similar to case 4, Figure 2b) was used, allowing up to 27.0$^{o}$ of tilt to be removed. When the tilt was restricted to 24.2$^{o}$, 2.59 twists were obtained in the second half of the dive. The sum of the two twists (5.71 rev) indicated that five twists should be possible with some margin (0.71 rev) to spare (Table 1). Simulated annealing found such a limiting dive (Figure 9, Figure 10) and other solutions with an arm abduction range of 15$^{o}$ in the twisting phase (Table 1).

The angular momentum requirement for the six dives ranged from 0.89 to 0.96 straight somersaults per second (Table 1) and was primarily dependent on the time spent with the body in an extended configuration.

Figure 9. Asymmetrical chest movement can produce up to five twists in a forward 1½ somersault dive (side view).

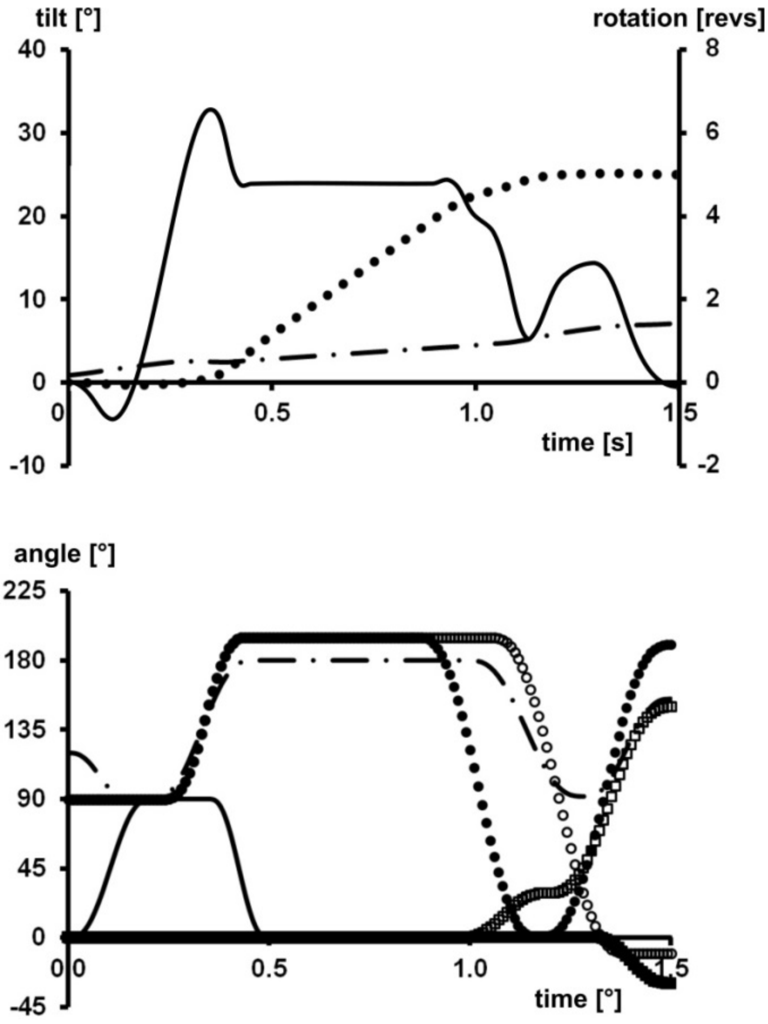


Figure 10. Somersault in revolutions (dashed line), tilt in degrees (solid line) and twist in revolutions (closed circles) during the forward 1½ somersault dive with five twists produced by asymmetrical chest movement (upper graph); chest torsion (solid line), hip flexion (dashed line), left arm abduction (open circles), right arm abduction (closed circles), left arm elevation (open square), and right arm elevation (closed squares) in degrees (lower graph).

**DISCUSSION**

The aim of this research study was to determine the limits of aerial twisting techniques comprising asymmetrical movements of arms, hips and chest in forward rotating 1½ somersault dives with twist. It was found that asymmetrical arm techniques were capable of producing between two and five twists, asymmetrical hip flexion up to three twists, and asymmetrical chest torsion up to five twists. For each of the six limiting dives there were nearby solutions with ranges of arm abduction in the twisting phase from $6^o$ to $17^o$. In the four asymmetrical arm cases it was assumed that the arms remained straight throughout the dive. During the twisting phase it is more usual for the elbows to be flexed as in the variation shown for case 3 (Figures 2a, 6). This variation allows a greater arm abduction range ($16^o$) than the $10^o$ for straight arms. In both the limiting dives with five twists (asymmetrical arms case 4 and asymmetrical chest) both arms are held above the head during the twisting phase. While this has the mechanical advantage of allowing more twists per somersault for a given tilt angle, there is likely to be some lack of acceptance in the diving community since this is not a traditional body configuration for twisting dives. Such resistance may disappear with the realisation that five twists can only be accommodated within 1½ somersaults by adopting this configuration. Currently the forward 1½ with quintuple twist has not been attempted in competition and has not been assigned a degree of difficulty. A previous suggestion as to how the dive might be accomplished (Tong & Dullin, 2016) is unrealistic due to the speed required for the arm movements. The current maximum number of twists in a forward 1½ somersault twisting dive performed in competition from the three metre springboard is four twists (FINA, 2017, Appendix 2).

The extent to which the various assumptions affect the results of this study will now be considered. In any performance of a given movement 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 six limiting dives there was some margin to allow compensation for variation in execution as indicated by the amounts of additional twist available (ranging from 0.38 to 0.76 twists) and the amounts of additional arm abduction available in the twisting phase (ranging from $6^o$ to $17^o$, Table 1). 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 fourth case of arm asymmetry, were each perturbed by 0.01 s (Hiley et al., 2013) to determine the effect on somersault and twist. In the perturbed simulation there was 9% less twist and 1% more somersault after 0.75 s. As a consequence there would need to be 10% twist margin for compensation. The twist margin for this dive was 0.44 which is just below this level. The twist margins for the other five dives were all greater than 10%.

The effects of combining techniques were investigated using optimisation. Introducing asymmetrical hip movement into the asymmetrical arm techniques increased the limiting dive in case 1 from two twists to three twists and left the remaining three limiting dives unchanged but with increased margins of 0.54 twists on average. Introducing asymmetrical arm adduction into the asymmetrical hip technique left the limiting dive unchanged at three twists but increased the twist margin by 0.55 twists. Introducing asymmetrical hips into the asymmetrical chest technique left the limiting dive unchanged at five twists but increased the twist margin by 0.29 twists. As a consequence the limiting dives with five twists (asymmetrical arms case 4 and asymmetrical chest) had twist margins of 16% and 20%.

The maximum joint angular velocities corresponding to the assumed minimum durations are lower than some values from the literature but this is probably a consequence of more rapid movement with flexed limbs than with straight limbs (Jessop & Pain, 2016) or a greater range of movement (Felton & King, 2016). Even so the lower bounds placed on the durations of arm and hip angle changes were based on actual performances and may possibly overestimate the minimum time needed for a joint movement. The effect of this was investigated by reducing all lower bounds on durations by 10% and the effects on optimisations determined. Tilt production increased by no more than $0.1^{o}$ in all cases. The twist margin for the six limiting dives increased on average by 0.30 twists but the limiting dives did not change. Although such timing changes may make the limiting dives easier, the 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. Thus the value of 1.5 s for the flight time is not a limitation of the study. 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 25.1 with arms together 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 the arms overhead configuration is clear. For comparison the inertia parameters of two other male competitive springboard divers (ratios: 16.5, 26.5; 19.1, 28.8) were used to determine the limiting dive for asymmetrical arm movement (case 4). It was found that the same limiting dive was obtained for both divers with arm adduction ranges in the twisting phase of $7^{o}$ and $12^{o}$ compared with the $7^{o}$ of the original diver and twist margins of 0.45 and 0.69 twists compared with 0.44 twists 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.

The model modification of allowing the shoulder centres to move as a function of the angle between arm and trunk had little effect on the amount of tilt produced but increased the inertia ratio with arms overhead by 10%, leading to 10% more twist in the twisting phase. In other applications in which both arms are not placed overhead, the difference arising from this modification will be much smaller.

In this study the criteria for attaining the final target angles of somersault, tilt and twist were that they should be met within $1^{o}$. This value was essentially arbitrary and variations within high scoring competition dives are likely to be somewhat greater than this. If the tolerance value were to be increased to $2^{o}$, for example, this would not change the limiting movements but would allow a greater range of arm abduction angle and hence more scope for adjusting an individual performance.

It can be concluded that in the aerial phase of a forward 1½ somersault dive, asymmetrical arm movement is capable of producing up to five twists, asymmetrical hip movement up to three twists, and asymmetrical chest movement up to five twists.

## 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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