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The control of twisting somersaults

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ABSTRACT

In the takeoff and early flight phase of a twisting somersault, joint coordination is based on feed-forward control whereas in the late stages of the flight phase configuration adjustments are made using feedback control to ensure accurate completion of the movement and appropriate landing orientation. The aim of this study was to use a computer simulation model of aerial movement to investigate the extent to which arm and hip movements can control twist and somersault rotation in the flight phase of a twisting somersault. Two mechanisms were considered for the control of twist in simulated target trampoline movements with flight times of 1.4 s. In the first case a single symmetrical arm adduction correction was made using delayed feedback control based on the difference between the twist rate in a perturbed simulation and the twist rate in a target movement comprising a forward somersault with 1½ twists. Final corrections were made using symmetrical arm abduction and hip flexion to adjust the twist and somersault angles. In the second case continual asymmetrical arm adduction/abduction adjustments were used to remove the tilt from a perturbed full twisting backward somersault using delayed feedback control based on twist angle and angular velocity. The first method was able to cope with perturbations to a forward somersault with 1½ twists providing the feedback time delay was less than 200 ms. The second method was able to correct a perturbed full twisting backward somersault providing the feedback time delay was less than 125 ms.

1. Introduction

Targeted movements in sport may be coordinated using feed-forward control as in the throwing of a dart in which the action is completely preplanned. Alternatively the sports participant may have to react to changing circumstances as in a tennis rally in which feedback control is used to coordinate movement. In acrobatic movements with a flight phase, feed-forward control is used for coordination in the takeoff and early part of the flight phase. In the latter stages of the flight phase, feedback control is used to adjust body configuration in order to obtain the intended appropriate target landing orientation.

In acrobatic sports such as gymnastics and trampolining, twist may be introduced into a somersault during the contact phase (Yeadon, 1993a, 1993b). Alternatively twist may be initiated during the aerial phase by means of asymmetrical arm or hip movements (Yeadon, 1993c, 1993d). Such mechanisms for achieving a targeted movement are typically learned by repeated attempts (Schmidt, 1975). These learned joint movements are not identical from performance to performance since there is always variability in the execution of coordinated movements. This coordination variability arises from planning errors, execution errors and noise in the motor-sensory system (van Beers et al., 2004; Cohen and Sternad, 2009; Bartlett et al., 2007). As a consequence the somersault and twist resulting from the configuration changes also has variability and some form of feedback control is needed to reduce this outcome variability (Hiley et al., 2013).

Estimates of joint angle variability obtained from repeated giant circles on high bar by an elite gymnast range from 1° to 3° (Hiley et al., 2013). Mean angular velocity variability over the last half circle on high bar prior to a Tkatchev release by an elite gymnast was 1.3% (Hiley and Yeadon, 2012). It might be expected therefore that release velocity and angular momentum about the mass centre would have similar variability and that rotation potential (the product of angular momentum and flight time) would have variability of around 2%. For a twisting somersault such variability in the initial conditions of flight may be expected to lead to similar variability in somersault but possibly greater variation in twist since joint movements will have a different effect when made at different twist values. It is to be expected that

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elite gymnasts will have lower variability in initial conditions and joint angle time histories and that this will lead to less variability in movement outcomes.

In the case of twisting somersaults the twist rate and somersault rate have the potential to be controlled using symmetrical changes in arm abduction and hip flexion. For aerial twists that arise from tilt produced by asymmetrical movements in the flight phase, the twist may be stopped prior to landing by removing the tilt at an integral number of half twists, again using asymmetrical movements of the arms and hips (Yeadon, 1993c). This provides another potential means for ensuring that the targeted final twist angle is achieved: by making adjustments to the tilt angle. The task of closely matching the intended target values of somersault, tilt and twist angles simultaneously at the time of landing is a complex one since configuration changes that affect one of these three angles also have some effect on the remaining two angles. The problem is aggravated by the inherent feedback system delay which can be up to 100 to 200 ms for long loop/triggered and voluntary responses (Latash, 1998). Thus any correction has to be based upon the state of the mechanical system at a previous time. As a consequence there will be limits to the level of control that can be exercised on the somersault and twist rotations.

When the landing area is viewed late in the flight phase there will be limited time in which to flex or extend the hips to adjust the somersault rate and hence orientation prior to landing. As a consequence it is likely that a single adjustment will be made. In contrast the build-up of twist in an unstable non-twisting straight double somersault may be controlled by asymmetrical arm movements using continual feedback throughout the flight phase (Yeadon and Mikulcik, 1996).

In this study the extent to which arm and hip movements can control twist and somersault during the aerial phase of a twisting somersault will be investigated for two hypothetical target movements using discrete and continuous automatic control schemes implemented within a computer simulation model of aerial movement (Yeadon et al., 1990).

2. Method

Two hypothetical simulated target movements were used to evaluate methods of controlling twist and somersault in aerial movements. Various perturbations were introduced into the original movements and in-flight corrections were made with the aim of achieving the target values of somersault, tilt and twist.

An 11-segment computer simulation model of aerial movement was used with the segmental inertia parameters of an elite trampolinist obtained from anthropometric measurements (Yeadon, 1990) to generate target simulations. The model had previously been evaluated against recorded performances in gymnastics: floor (Yeadon and Kerwin, 1999), high bar (Yeadon, 1997), rings (Yeadon, 1994), trampolining (Yeadon et al., 1990), diving (Yeadon, 1993e) and the aerials event in freestyle skiing (Yeadon, 1989).

2.1. Discrete control

The first target movement had duration 1.4 s and comprised a forward somersault with 1½ twists (as used in trampolining) produced by asymmetrical movement of the hips in the aerial phase (Fig. 1). The body moved from a forward hips flexed position with arms abducted through side flexion over the right hip before extending to a straight body configuration, resulting in a twist to the left (Yeadon, 1993c). The minimum angle between the upper trunk and the thighs was 128°. The arm abduction angle during the middle phase in which the body was held straight was 9°. The tilt was removed using asymmetrical hip movement in which the body moved from a side flexed position over the left hip into a forward hips flexed position. As a consequence the twist stopped. Angle changes were made using a quintic function with zero first and second derivatives (Hiley and Yeadon, 2003).

Four perturbations were introduced into the twisting somersault using the variation levels described in the Introduction. In the first perturbation the maximum hip flexion was reduced by 2°, resulting in a decrease in the maximum tilt angle from 12.5° to 11.5°, a decrease in the final twist angle from 540° to 501° and a decrease in the final somersault angle of 14°. In the second perturbation hip flexion was increased by 2°, resulting in an increase in the maximum tilt angle from 12.5° to 13.4°, an increase in the final twist angle from 540° to 618° and an increase in the final somersault angle of 6°. In the third perturbation the (somersault) angular momentum was decreased by 2%, resulting in reductions of 0.3°, 23° and 13° in tilt, twist and somersault. In the fourth perturbation the somersault momentum was increased by 2%, resulting in increases of 0.2°, 31° and 10° in tilt, twist and somersault.

The twist rate $\dot{\psi}$ about the longitudinal axis of an axially symmetric body is given by $\dot{\psi} = [h/C - h/A] \sin\theta$ where h is the total angular momentum about the mass centre, A is the transverse moment of inertia, C is the longitudinal moment of inertia and θ is the tilt angle (Yeadon, 1993a). Thus adducting the arms during the central phase of the movement when the body is straight will produce a twist rate proportional to $[1/C - 1/A]$. A decrease in arm adduction of 1° from the 9° in the target movement will correspond to an increase of 2% in the twist rate.

In order to correct for a perturbation there are the added complications of a shortfall of twist prior to the middle phase as well as the delay in feeding back twist rate information. The scheme for correcting for the twist error arising from a perturbation comprised changing the arm adduction angle in proportion to the percentage difference between the perceived twist rate in the perturbed simulation compared with that of the target movement at the time of the start of the middle phase with arms adducted at 9° from the body. The adduction arm angles were each increased by δ where:

$$\delta = p(\dot{\psi}/\dot{\psi}_T)$$

with p the constant of proportionality, $\dot{\psi}$ the twist rate at the start of the middle phase with arm abduction equal to 9°, and $\dot{\psi}_T$ the corresponding twist rate in the target movement. A quintic function with zero first and second derivatives was used to make the change in arm angle (Hiley and Yeadon, 2003). A time delay of 200 ms was used and so the arm angle did not start to change until 200 ms after the start of the middle phase. The duration of this (small) arm movement was set at 100 ms. The last 100 ms of the middle phase was used to reset the arm adduction angle to 9°.

Constants of proportionality for the correction each of the four perturbations were determined (empirically) in order that the final twist angle matched the target value of 540°. Since a gymnast cannot tailor such a constant to an individual perturbation an average value was taken and corrective simulations were run again for the four perturbations. While the effects of the perturbations were reduced, the final twist angles no longer matched the target value. Additionally there were errors in the final somersault angle that would have made landing on trampoline less than ideal.

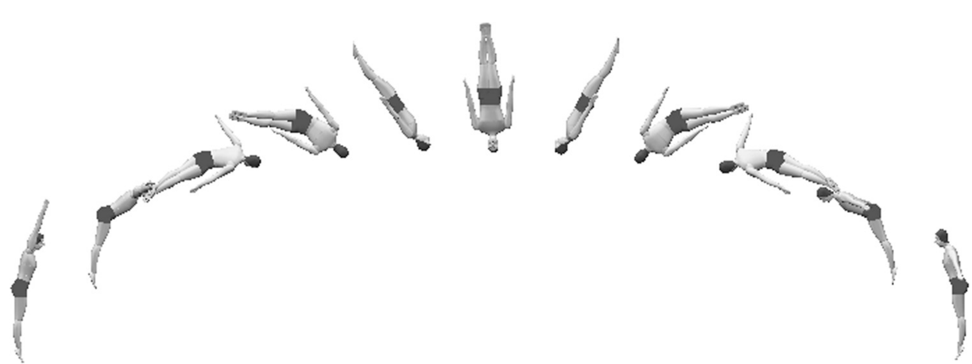

Fig. 1. Forward 1½ twisting somersault target simulation with a flight time of 1.4 s.