RELATIVE CONTRIBUTION OF CONTACT AND AERIAL COMPONENTS IN THE CONTROL OF AERIAL ROTATION TO GUIDE ACROBATICS SKILLS LEARNING

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The contribution of release state, change in inertia moment, and angular momentum transfer to the performance of a transition move on asymmetrical bars was analysed to better guide acrobatics learning in novices and experts. Numerical simulation based on actual release state was used to optimise aerial technique in novices and experts. Optimised novice performances did not reach actual expert ones. Thereafter, it may be crucial to orient novice learning toward improving release state. In addition for both groups, adjustments of inertia moment and momentum transfer in optimised techniques significantly increased performances. Finally in all actual or optimised techniques, the level of contribution of inertia moment correlated the most with the level of performance. Therefore technique enabling larger change in inertia moment should be preferred.

KEY WORDS: acrobatics learning, sport performance, aerial dynamics, dynamic optimisation.

INTRODUCTION: In acrobatic sports, the main objective is to master movements with rotations performed during an aerial phase. The trajectory and rotation potential of the gymnast during this aerial phase is the result of a push-off phase or a swing, during which linear and angular momenta are determined. Therefore learning of most acrobatic skills often focus on push-off phase, assuming that appropriate take-off conditions allow smaller room for failure. These are indeed mandatory to manage the skill, but they are not always the most or only decisive factors to master the skill. Control of the rotation during the aerial phase is also a complex task that requires a specific learning for acrobatics sports. Both release state and aerial joint kinematics were found to differ in various extends between experts and novices in acrobatics (Prassas, 1995). In aerial phase, body rotation can be controlled by change in inertia moment and angular momentum transfers between the segments. The analysis of these contributions in expert *versus* novice gymnast performances could direct learning towards more effective and safer methods (Yeadon, 1997).

Computer simulation can be used to modify or optimise take-off state and aerial joint kinematics to estimate their relative contribution to the performance and better understand how to effectively perform a skill. The counter movement forward in flight (CMFIF) is a simple transition move in uneven bars described as an “underswing on lower bar with counter movement forward in flight to hang high bar” (FIG). Novices can rapidly learn this skill, however their body rotation angle at re-grasp is insufficient to swing and perform an upstart in sequence causing a large penalty. Based on the expert sub-optimal technique (Huchez, Haering, Holvoët, Barbier, & Begon, 2013), three combined strategies helped improve performance: 1) increase hip flexion-abduction to reduced transverse moment of inertia, 2) transfer leg and arm angular momenta to the increase forward rotation of the trunk and 3) a straighter hand path to the bar. However, results were not applied to novices and relative contributions of release state, moment of inertia variation and angular momenta transfers were not quantified.

The main objective was to assess acrobatics performance factors (*i.e.* release state, moment of inertia and the segmental angular momenta transfer) in accordance to the expertise level for actual and maximal (obtained by dynamic optimisation) performances. We hypothesized that novice gymnasts do not manage to successfully perform the CMFIF mainly because of aerial joint kinematics state rather than release state.

METHODS: Seven expert and seven novice female gymnasts performed three trials of CMFIFs in sequence with an upstart if possible. The uneven bars were setup in line with the competition rules. The kinematics of 33 markers placed on gymnasts and 4 markers locating uneven bars were recorded during all trials using a motion analysis system (Vicon T20 @250 Hz). All participants and their parents for underage subjects gave their inform consent in agreement with the local ethics committee. Three-dimensional joint kinematics of a 14-segments multibody system (i.e. trunk, head, arm, forearm, hand, thigh, shank and foot of left and right sides) were computed following ISB recommendations.

An angle driven model was developed (Huchez et al., 2013) to generate aerial techniques for expert and novice gymnasts. For simulation purpose, knee, ankle, neck and wrist joint angles were fixed, movement of the trunk was assumed planar, and upper and lower limbs were actuated symmetrically throughout aerial phase. As root segment, the trunk was attributed with three DoFs, $q1$, (forward and vertical translations, and forward rotation) to be solved by forward dynamics. The hip flexion and abduction, the shoulder plane of elevation, forward elevation and rotation, and the elbow flexion and prono-supination were seven additional DoFs, $q2$, driven by the reconstructed joint kinematics of recorded trials. Acceleration of the root segment $\ddot{q}1$ was solved through an Euler-Lagrange inverse dynamics equation function of previous state $\mathrm{x(t)} = [\mathrm{q}^{\mathrm{t-1}}, \dot{\mathrm{q}}^{\mathrm{t-1}}]^{\mathrm{T}}$ and joint kinematics input, $\ddot{q}2$. This ordinary differential equation (ODE) of the multibody system is integrated in a 4-5th order Runge-Kutta algorithm from the release state $x^0 = [\mathrm{q}^0, \dot{\mathrm{q}}^0]^{\mathrm{T}}$. Final time is defined as an event equation in the ODE solver, which corresponds with either the gymnast catching high bar or her wrists passing high bar vertical plane.

A single cubic splines parametric optimization was used to obtain in-flight kinematics that maximizes the horizontal distance between the high bar and the center of mass: $J = \min_{[q2,t]} G_H^T$ was obtained from each real kinematics with nonlinear constraints. Successful re-grasp is defined by wrist back under the bar and finger joint in front above it, the hand mediolateral axis collinear (±40°) to the bar, and hand to hand distance between 0.2 and 0.6 m (Huchez et al., 2013). Leg intersections with lower-arm or bar are avoided using a line-cylinder intersection algorithm where leg was a line segment and lower-arm or bar were 3 or 2 cm diameter cylinder respectively. The shoulder range of motion was constrained to remain inside a ZXZ non-convex hull (Haering, Raison, & Begon, 2014) discretized to provide distance from joint limit for every cubic degree pose. Joint torques were also limited based on a female gymnast isokinetic measurements (Sheets & Hubbard, 2009) to ensure realistic joint accelerations.

For initial and optimal kinematics of all trials, a performance score was calculated as the horizontal distance of the CoM at re-grasp (time t=T) from the upper bar (Huchez et al., 2013). This distance, G_H^T, is the moment arm of the weight around the bar initiating backward swing after the aerial forward rotation. Then, the rotation of the trunk completed during the flight (θ_f) which highly correlates with the horizontal distance of the CoM at re-grasp, was used to identify three components of the performance: rotation due to the release state (θ_{RS}), additional rotation due to the change in moment of inertia ($\theta_{\Delta I}$) and complementary rotation from transfer of angular momentum between upper limbs, lower limbs, and trunk (θ_{TR}). These components were calculated using angular velocity of the body at release (ω_i=σ_i / I_i) and the moment of inertia time history ($I(t)$) such as:

$$\theta_{RS} = \theta_f - \omega_i(t_f - t_i), \quad (1a)$$

$$\theta_{\Delta \mathrm{I}} = \int_{t_i}^{t_f} \frac{\sigma_i}{\mathrm{I}(t)} dt - \theta_{RS}, \quad (1b)$$

$$\theta_{\mathrm{TR}} = \theta_f - (\theta_{RS} + \theta_{\Delta \mathrm{I}}). \quad (1c)$$

Correlation coefficient between performance and the three aerial rotation components were computed. The effect of expertise and optimization on the relative contribution of these three components to final rotation were tested with a one-way repeated-measures ANOVA followed by Bonferroni post-hoc analysis.

RESULTS: When looking at initial kinematics of all trials (Fig. 1), change in moment of inertia has the smallest (sometimes negative) contribution of the three components to the total rotation, however its value and therefore its contribution increases the most with performance. On average, momentum transfer has the greatest contribution of all. Correlation coefficients of r=0.74, 0.75, and 0.30 were found between actual performance and either moment of inertia change, momentum transfer or release state. Inversely, with optimal kinematics the relative contribution of the three components is more balanced and less variable. Correlation coefficients of r=0.64, 0.73, and 0.33 also demonstrated moment of inertia is the most related with improved performance.

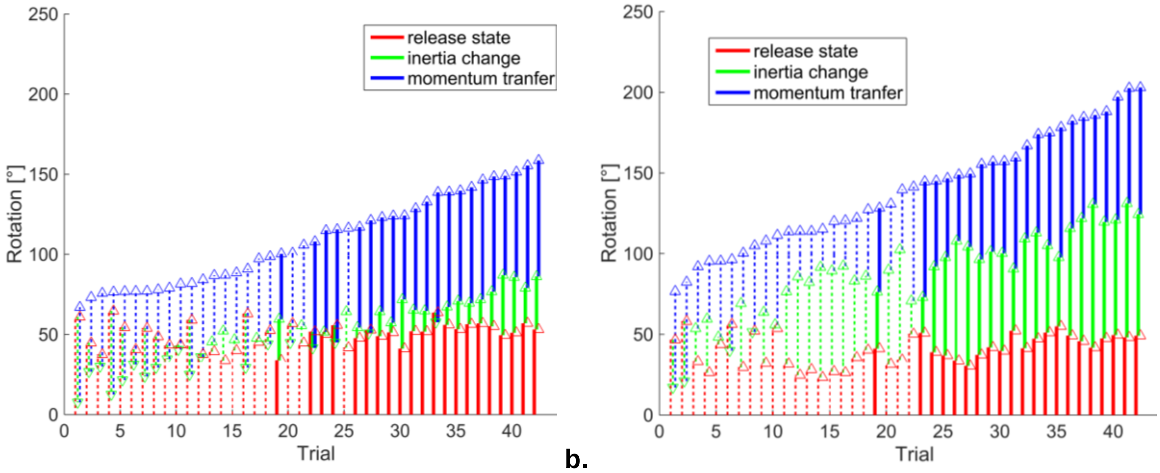

Figure 1: Relative contribution of release state (red), positive or negative (when colour bars overlap) change in inertia (green) and angular momentum transfer (blue) to the final rotation in all recorded trial in order of increased performance for novices (dashed) or experts (solid) during a. actual and b. optimized performances.

In table 1, novice and expert gymnasts could improve significantly their performance from initial to optimal technique (p<0.001). Moreover, novice initial and optimal performances are significantly lower than expert performances (p<0.001). Besides, release state contribute to more than half or a third to the total rotation for all but the expert optimal solutions where its contribution is down to a quarter. Inversely, moment of inertia change and momentum transfers have both significantly larger contributions in experts than novices (p<0.001). Nevertheless, momentum transfer has a much smaller standard deviation values than moment of inertia reduction. Finally, the relative contributions of release state, moment of inertia change and momentum transfer are almost the same in optimized solutions.

Table 1: Comparison of novices and experts score and body rotation due to release state θ_{RS}, moment of inertia change $\theta_{\Delta I}$, and momentum transfer θ_{TR} contributions to total rotation angle θ_f for initial and optimal kinematics. Statistical significant differences with novice initial (^{1}) or optimal (^{2}), expert initial (^{3}) or optimal (^{4}), and all (***) kinematics are highlighted with exponent indices.

	Novices		Experts	
	Initial	Optimal	Initial	Optimal
G_H (m)	0.01±0.09^{3,4}	-0.10±0.10^{3,4}	-0.25±0.10***	-0.30±0.08***
θ_f (°)	85.7±12.2***	110.5±17.2***	132.3±16.4***	168.1±21.2***
θ_{RS} (°)	47.9±9.2^{3,4}	37.4±11.3^{4}	51.9±6.1^{1}	44.2±6.6^{1,2}
$\theta_{\Delta I}$ (°)	-12.2±21.1^{3,4}	30.7±32.6^{3,4}	13.8±14.2***	62.0±16.6***
θ_{TR} (°)	50.0±7.4*^{3,4}	42.4±12.7*^{3,4}	66.7±8.7*^{1,2}	61.9±10.9*^{1,2}

DISCUSSION: This study estimated the relative contributions of contact and aerial technique components to the total rotation performed in CMFIF. Correlations indicate that performance in expert and novice gymnast trials is mainly influenced by variation in momentum transfers and moment of inertia reduction. The momentum transfer is the most important contributor to aerial rotation angle in all novice and expert performances, while moment of inertia management is probably the one allowing larger room for improvement. In fact, a slightly smaller contribution to total aerial rotation is observed in non-optimized kinematics and very large standard deviations are observed in all kinematics except for expert optimised performances.

With optimal in-flight joint kinematics, the novice performance remains inferior to expert actual performance. The release state contribution should be interpreted with caution. In effect, the same body rotation can be obtained with a large angular momentum and a short aerial phase (novices) or inversely (experts). Since the duration of the CMFIF is highly constrained by the end-point, *i.e.* catching the bar, the release state should receive additional attention in future studies. The in-flight duration could be a key factor to change moment of inertia and momentum transfer.

Results of the present study suggest that both novices and experts gymnasts would significantly increase their performance by improving their technique in-flight and especially by increasing their moment of inertia reduction. In novices however, the gap between optimized novice and expert initial performances remains as large and significant as the one filled by optimising aerial technique. At first sight, the needs for contact and aerial technique refinements can be considered equally in novice gymnasts which does not confirm our hypothesis. Nevertheless, the large variability observed in real and optimized novice technique may indicate that individualized conclusion might be more appropriate. In expert gymnasts, since optimal solution obtained respect physiological constraints based on gymnasts measurement, the significant difference found between real and optimized expert performances may be explained because gymnasts from the present study were experts in gymnastics, but had not practiced the CMFIF for a long time before the study.

Finally, in optimal techniques, a balance between the three components contributions seems to be reached. Therefore, it can be hypothesized than an estimation of the relative contribution of those three factors averaged over several trials may help coaches to identify individual gymnast's need for acrobatic skills improvement.

CONCLUSION: Assessing the mechanical components of the body rotation is recommended to personalize acrobatic skills learning toward a balanced contribution of the three components. This contribution varied between novice and expert gymnasts, but also between actual and optimized techniques. Findings suggest that novices should be coached on both contact and aerial technique, since their optimal performance is lower than expert actual performance. Experts should mainly improve their aerial technique. In general, technique enabling larger change in inertia moment should be preferred.

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