DIFFERENCES BETWEEN EXPERT AND NOVICE GYMNASTS PERFORMANCE OF A COUNTER MOVEMENT FORWARD IN FLIGHT ON UNEVEN BARS

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Abstract

This study investigated the different strategies exhibited by expert and novice gymnasts in counter movement forward in flight on uneven bars. Eleven gymnasts performed three trials connected with a kip to support. The gymnasts were divided into two groups according to their ability to connect: six able (termed as experts) versus five non-able (novices). The 3D motion data were collected at 250 Hz. Biomechanical parameters were computed at release (release state and angular momentum), during aerial phase (duration, minimum value of the moment of inertia) and at regrasp (total duration and rotation angle). Robustness of the release state was also compared. Significant differences were found between groups in the three phases. The novice gymnasts performed as robustly as expert gymnasts but less efficiently because they released the low bar before their centre of mass passed the horizontal, with a lower vertical velocity, resulting in a lower and shorter aerial phase. They also had a larger minimum moment of inertia in flight. Coaches could help novice gymnasts to decrease their dependency on their robust technique by improving the release angle. Exercises, which may allow novice gymnasts to exceed the threshold of a 90° rotation angle at release are suggested.

Keywords: *technique, expertise, counter movement forward in flight, kinematics.*

INTRODUCTION

Gymnasts can perform the same skill independently or as a part of a sequence. Additional constraints appear when the skill is performed as a part of a sequence. Indeed, the final body state of the first element (*i.e.,* the position, the configuration and their speed) must lead to the initial state of the following skill. A few adaptations are thus required in both the push-off and aerial phases of the first element to adjust the linear and angular momenta between the two elements (*i.e.,* during the connection phase; Hmed & Hassan, 2010; Sadowski, Boloban, Mastalerz, & Niznikowski, 2009). For example, Sadowski et al. (2009) found differences in body rotation angle at landing, and in hip flexion (at landing and in the last half revolution) when comparing a double backward layout somersault performed with stable landing or in combination with a whip somersault. Connecting acrobatic skills is a technical development trend in gymnastics (Han, Xu, Dai, & Chang, 2008) and a characteristic of expertise. In particular, in bars routines, any break between two moves results in up to a 0.5 point deduction in competition, while connecting difficult elements awards additional points (FIG, 2013). Thus, coaches have to plan a technically possible progression, allowing gymnasts not only the opportunity to perform the skill but also to execute the skills in sequence in their routine. Previous researches focused on adaptations of landing to connect skills (Hmed & Hassan, 2010; Sadowski et al., 2009). Nevertheless to the best of our knowledge, the connection of skills on uneven bars has not been studied yet.

On the uneven bars and the high bar, among the elements that can be included in sequence in a routine are the release-regrasp elements. Combined with their preparatory giant circles, these elements have received attention due to the number of related injuries (Brüggemann, Cheetham, Alp, & Arampatzis, 1994; Gervais & Tally, 1993). When several techniques can be used to perform a skill, coaches are interested in identifying which technique is the most suitable for safety, success and connection. Previous studies have highlighted not only biomechanical factors of performance but also motor control aspects, such as the robustness of the technique, that affect both the kinematic variability among athletes (Hiley & Yeadon 2012; Yeadon & Brewin 2003) and the consideration of the consequences of failure (Bradshaw & Hume, 2012; Yeadon, 1999). Hiley and Yeadon (2003) showed that a scooped giant circle is a more robust dismount technique because the acceptable margin of error at release is 48% greater than in traditional techniques. In terms of failure consequences and connection problems, Kerwin, Irwin and Exell (2007) and Kerwin and Irwin (2010) compared inward and outward techniques of the Tkachev. The differences between the two techniques are due to the low bar, which represents a double geometric constraint in the outward technique. The gymnast has to avoid the bar in the giant circle not only before the Tkatchev but also after regrasping or if unexpectedly missing the high bar. With the inward technique, the angular momentum is larger, and the regrasp occurs earlier to facilitate connections (Kerwin et al., 2007). Thus, gymnasts do not use the same technique according to the consequences of a possible failure. Considering the effect of the technique on failure consequences, Yeadon (1999) discussed the dynamics at landing for different twisting somersault techniques. In contact twists, the angular momentum around the longitudinal axis is constant until the landing and could lead to greater ankle and knee injuries (Yeadon, 1993a). This is a disadvantage in comparison with the aerial twist technique (Yeadon, 1993b). Better understanding techniques from a biomechanical perspective can help coaches to identify which technique is the most suitable for safety, success and connection. This can be achieved by comparing experts and novices performing the same skill.

On the uneven bars, the “counter movement forward in flight” (Figure 1) is an element that requires reversing the direction of rotation twice when performed in combination with a kip to support. It involves a backward rotation around low bar, a first reversal of rotation around the body centre of mass shortly before grip release, a forward rotation in flight, and a second rotation reversal to swing backward around high bar. It belongs to the transition elements (*i.e.* flight elements between low and high bars). It is performed in approximately 70% of the routines at all levels of competition (Tordi, 2006). However, it is performed without deductions by the judges in only 30% of cases. Whereas advanced gymnasts execute the dual task of grasping the high bar while creating enough swing potential to link the counter movement forward in flight with a kip to support skill, beginners typically only perform the counter movement forward in flight as a catching task. Their technique can be observed as a derivative of the underswing dismount (Figure 2). At regrasp, deductions are applied if the shoulder level is lower than the upper bar (0.3 point, in the FIG code of points, 2014; p. 51-52) and if the feet are passed the vertical position of the shoulders (0.1 point). Therefore experts **are expected to produce larger vertical** component of the centre of mass trajectory, and complete larger transversal rotation in flight to avoid such deductions. Moreover, a limited swing can lead to a lack of rhythm in the kip to support execution (0.1 point) or an additional swing (0.5 point). Thus, a proper understanding of the joint actions and centre of mass trajectory that ensure the counter movement forward in flight to kip to support connection without deductions is a requirement for gymnastics coaches.

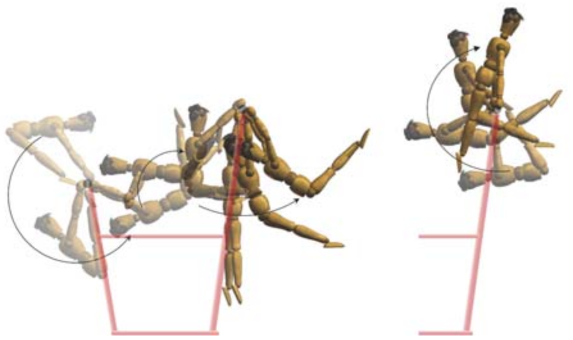

Figure 1. The counter-movement forward in flight on uneven bars in connection with a kip to support. Arrows indicate the rotation direction throughout the sequence.

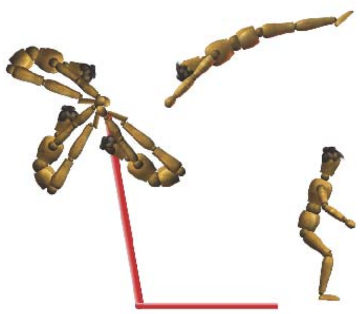

Figure 2. Toes on underswing dismount.

The purpose of the current study was to investigate control of counter movement forward in flight in expert and novice gymnasts. We hypothesised that expert gymnasts would perform better than novice gymnasts and succeed in the combination with a kip to support, by showing a more vertically oriented velocity at release and achieve a greater transversal rotation angle in flight thanks to adjustments of their moment of inertia and segment momenta. We also hypothesised that novice gymnasts would not show a higher variability of the biomechanical parameters at release, compared to expert gymnasts, since their technique would be robust and a derivative of the underswing dismount (Figure 2).

METHODS

Six expert national-level (13.7±2.9 years, 1.51±0.08 m, 42.5±10.1 kg) and five novice (20.5±2.3 years, 1.66±0.07 m, 56.1±6.6 kg) female gymnasts participated in this experiment. The inclusion criterion for the expert group was to be able to consistently perform the counter movement forward in flight in combination with a kip to support. The inclusion criteria for the novice group were specified as follows: (a) to have recently learned the counter movement forward in flight; (b) to be unable to connect with a kip to support; and (c) to be able to perform the kip to support independently. All participants, or their legal guardians, gave their informed consent in line with the guidelines set by the local ethics committee.

After warm up, all gymnasts were instructed to perform three repetitions of a counter movement forward in flight and kip to support continuously. Between trials, they had a rest period of self-chosen duration.

A 10-camera motion capture system (T-20 cameras, Vicon®, Oxford, UK) covering a 5 x 6 x 3.5 m^3 volume was sampled at 250 Hz to collect 3-D trajectories of markers placed on each participant. Thirty-five reflective markers defined fourteen segments in line with the anthropometric model of De Leva (1996): trunk, head, upper arms, forearms, hands, thighs, shanks, and feet, as detailed in Figure 3. The locations of each segment (chosen to minimize marker occlusions during the skill) are listed as the following anatomical landmarks: forehead, chin, bilateral acromion process, lateral epicondyles of the humerus, ulnar styloid processes, second and fifth metacarpals heads, greater trochanters, lateral epicondyles of femurs, lateral malleoli of ankles, fifth metatarsal heads, tuber calcanei, forehead, chin, temples, spinous processes of C7, T5, T12, and posterior superior iliac spines. Eight additional markers were placed at the midpoints of the arms, forearms, thighs and shanks.

For all gymnasts, the bars were set at their maximum standard width (1.80 m).

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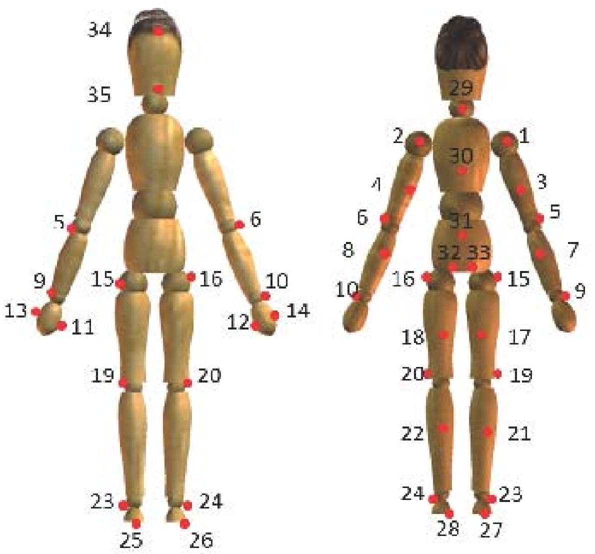

Figure 3. Set of 35 markers placed on the major processes of the right (1) and left humeri (2), posterior mid-arm (3, 4), lateral epicondyle of the right (5) and left humeri (6), posterior mid forearm (7, 8), right (9) and left (10) ulnar styloid processes, second (11, 12) and fifth metacarpals (13, 14), major trochanters (15, 16), posterior mid-thigh (17, 18), lateral epicondyles of femurs (19, 20), posterior mid-shank (21, 22), external malleolus (23, 24), fifth metatarsal (25, 26), tuber calcanei (27, 28), spinous processes of C7 (29), T5 (30), T12 (31), iliac spines postero-superior (32, 33), forehead (34) and chin (35).

This placement was chosen to minimise marker occlusions during the skill.

For analysis, the task was divided into three phases: (a) the release of the low bar phase, (b) the aerial phase, and (c) the regrasp of the high bar phase. Based on a frequency analysis, the position data were filtered with a zero-lag second-order Butterworth filter with a cut-off frequency of 6 Hz (Winter, 1990). In case of occultation of a marker, a spline function provided in the interpolation plug-in of the Vicon Nexus® software was used to complete the missing part of the trajectory of the marker. The joint angles were calculated according to ISB recommendations (Wu et al., 2002, 2005). A quasi-planar analysis was conducted since bilateral symmetry of movement was assumed. Hip and shoulder angle time histories were differentiated using a centred difference method to create angular velocity profiles. The anthropometric model of De Leva (1996) was combined with segment kinematics to calculate the body centre of mass, the body moment of inertia along the transverse (medial-lateral) axis, and the transverse component of the angular momentum with respect to centre of mass. Preliminary analysis revealed that the error percentage on the acceleration of body centre of mass in the airborne phase was estimated to be approximately 6%. To compare gymnasts of varying sizes, angular momentum and minimum moment of inertia in flight were normalized (Kerwin & Irwin, 2010). Therefore, both were divided by the theoretical maximum moment of inertia (when the gymnast hangs from the high bar in a straight position) and angular momentum was further divided by the potential of revolutions per second in the same posture

The release and regrasp times were manually determined based on mid-hand markers with respect to the markers on the bars and their displacement due to hand release and contact. The body rotation angle at release was evaluated in the sagittal plane as the angle between the global vertical axis passing through the low bar and the line from the low bar to the body centre of mass position at the instant of the low bar release

(Figure 4A). The angle of release was defined as the angle between the horizontal and the release velocity vector in the sagittal plane (Figure 4B). Computing the body rotation angle in flight and the release angle is of particular interest since these parameters determine both the height and range of the trajectory of the body centre of mass. The aerial phase duration, the position of the body mass centre at apex and the total rotation angle of the body during the aerial phase were computed. The rotation angle at regrasp was defined as the angle between the global vertical axis passing through the high bar and the line joining the centre of mass of the gymnast to the neutral bar position (Figure 4C). To assess the deduction at regrasp, the shoulder height relative to the high bar (Figure 4D) and the ankle antero-posterior position relative to the shoulders (Figure 4E) were reported.

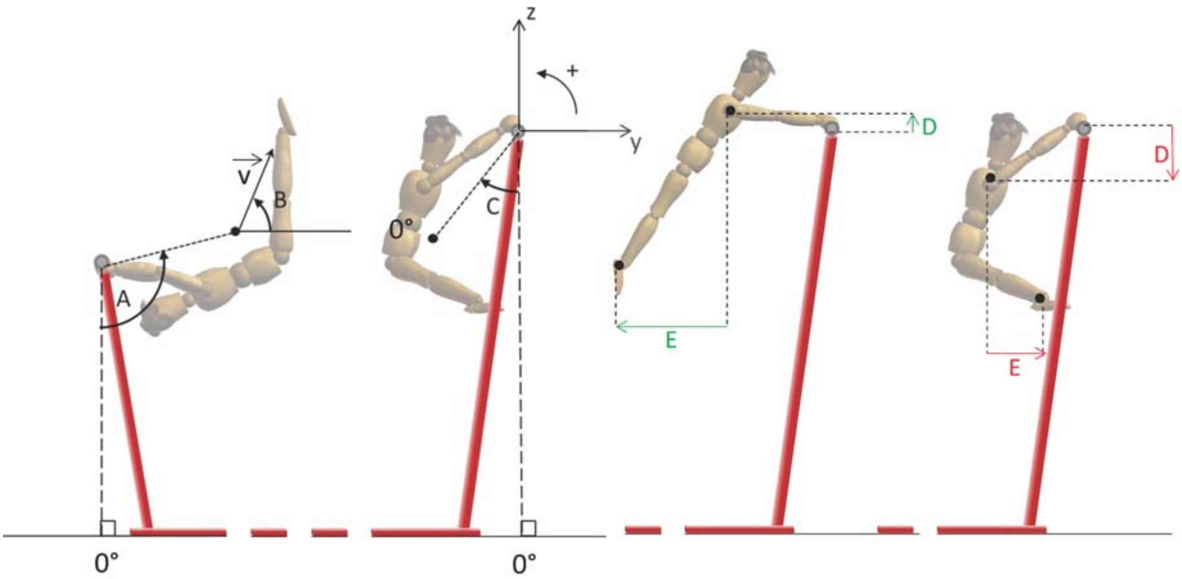

Figure 4. Definition of main angles, namely the rotation angle at release (A), angle of release (B) and rotation angle at regrasp (C). Deduction criteria: shoulders height *wrt* high bar (D) and ankle antero-posterior position *wrt* shoulders (E) are shown in the middle (no deduction) and on the right (deduction).

The mean values of the release parameters (the shoulder and hip flexion angles and velocities, the release angle, the body rotation angle, and the norm of release velocity), the normalised angular momentum, the minimum value of the transverse moment of inertia in flight, the total aerial phase duration, and the rotation angle at regrasp were calculated and compared using non-parametric Mann-Whitney U-tests. Afterwards, the effect size measure for non-parametric analysis was calculated, defined as $r=Z/\sqrt{N}$, where r represents the effect size, Z is derived from the conversion of the Mann-Whitney test and N is the total number of observations. This analysis considers r-values as: small effect size (r=0.10), medium effect size (r=0.30) or large effect size (r=0.50) (Field, 2005). To investigate whether the technique performed by the novice gymnasts is as robust as the technique of the experts despite their poorer experience, the intra-participant variability of the release state was investigated by determining the coefficients of variation of the release parameters. Mann-Whitney U-tests were used to compare the coefficients of variation between expert and novice groups. All statistical tests were performed (Statistica® Software 6.0, StatSoft, USA) with a significance level set at $\alpha=0.05$.

RESULTS

Low Bar Release

At release, neither the hip nor shoulder angles significantly differed between the two groups (p=0.07 and p=0.33, respectively; Table 1). However, the novice group showed a greater hip flexion velocity compared with the expert group (p<0.05). The expert group showed a larger angle of release (p<0.01) and a larger rotation angle (p<0.001). However, the release velocity norm (p=0.43) and the normalised transversal angular momentum (p=0.18) were similar between groups. In summary, expert gymnasts released the bar above horizontal with a larger vertical velocity than novice gymnasts. The coefficients of variation of the parameters at release (e.g., the hip and shoulder flexion and velocities, release angle, rotation angle at release and norm of release velocity) did not show any significant difference (all p>0.05) between the groups, as summarised in Table 2.

Table 1

Means and standard deviations for biomechanical and temporal variables at release, in flight and at regrasp. The last three columns are the between-group comparisons.

		Experts	Novices	**U**	***p***	***r***
Release	Shoulder flexion angle (°)	-32±7	-37±6	9	0.33	
	Hip flexion angle (°)	48±14	44±31	12	0.07	
	Shoulder flexion velocity (°/s)	554±323	451±185	10	0.43	
	Hip flexion velocity (°/s)	-159±100	-315±139	3*	0.03	0.66
	Release angle (°)	68±7	56±5	1*	0.00	0.77
	Rotation angle at release (°)	97±5	81±6	0*	0.01	0.82
	Norm of release velocity (m/s)	2.53±0.30	2.39±0.28	10	0.43	
	L_x (rev/s)	2.19±0.20	2.38±0.27	7	0.18	
Flight	Horizontal BCM position at apex (m)	0.91±0.20	1.09±0.08	6	0.12	
	Vertical BCM position at apex (m)	1.80±0.13	1.56±0.06	0*	0.00	0.82
	Total duration (ms)	440±46	365±14	0*	0.00	-0.82
	I_{min} (normalised)	0.47±0.06	0.60±0.08	3*	0.03	-0.66
Regrasp	Rotation angle at regrasp (°)	-39±10	-15±5	0*	0.00	0.82
	Shoulder height wrt high bar (cm)	-22±8	-46±5	2*	0.00	1.45
	Ankle antero-posterior position wrt shoulders (cm)	31±14	60±15	16*	0.00	-1.33
	Total rotation (°)	136±15	96±10	0*	0.00	0.82

Note: **(***) p<0.05. (L_x) corresponds to the normalised transversal angular momentum about the mass centre at release. (I_{min} normalised) is the normalised minimal value of the transverse moment of inertia. (BCM) is an acronym for body centre of mass, wrt is an acronym for with respect to.

Table 2
Means and standard deviations for coefficients of variation (dimensionless) with between-group comparison statistics.

	Experts	Novices	U	*p*
Shoulder flexion angle	0.12±0.05	0.12±0.06	11	0.84
Hip flexion angle	0.03±0.58	0.10±0.84	12	1.00
Shoulder flexion velocity	0.45±0.42	0.32±0.14	11	0.84
Hip flexion velocity	0.48±0.62	0.34±0.08	8	0.42
Release angle	0.07±0.04	0.06±0.03	11	0.84
Rotation angle at release	0.05±0.02	0.03±0.02	6	0.22
Norm of release velocity	0.06±0.03	0.07±0.03	7	0.31

Note: (*) p<0.05

Aerial Phase

The release state differences resulted in a higher centre of mass at the apex for the expert group in the aerial phase, (p<0.001). The expert group also spent significantly more time during the aerial phase (p=0.00). In addition, the expert gymnasts had a significantly smaller minimal value of the normalised transverse moment of inertia in flight compared with novice gymnasts (p<0.05).

High Bar Regrasp

At regrasp, expert gymnasts had a significantly larger rotation angle by 24° (p<0.001). Novice gymnasts had a lower shoulder height (p<0.001) and the average position of their feet was further ahead of the position of their shoulders compared with expert gymnasts (p<0.001). According to competition scoring guidelines, all gymnasts (excluding two in expert group) had a 0.3 point deduction for a lower shoulder height and a 0.1 point deduction for feet position beyond the vertical of the shoulders. The expert group had a larger total rotation (p<0.001).

In all cases, the effect sizes were greater than 0.5, indicating a “large” effect according to Field (2005).

DISCUSSION

Having the technical knowledge to make their gymnasts able to connect skills without deductions is a challenge for coaches. To fully understand the conditions allowing the connection of the counter movement forward in flight with a kip to support, we investigated kinematics of gymnasts able or not to successfully execute the sequence (expert and novice groups, respectively). The technique used by expert gymnasts allowed them to link the counter movement forward in flight to a kip to support thanks to a higher rotation angle at regrasp compared to novice gymnasts. This higher rotation angle at regrasp is the consequence of releasing the bar after the centre of mass passed the horizontal with a larger vertical velocity, and of a smaller minimum moment of inertia in flight.

Mechanical Requirements to Perform a Successful Connection

Between the groups, counter movement forward in flight techniques differed at take-off, in the aerial phase and at regrasp. Given their large effect sizes, the rotation angle at release, the angle of release and the minimal value of the inertia moment in flight afforded the most significant reasons why expert gymnasts succeeded and novice gymnasts did not succeed in connecting counter movement forward in flight with a kip to support. The expert gymnasts released the low bar above horizontal with a more vertically oriented velocity, resulting in longer flight duration and a higher parabola. In addition, they were able to further reduce their transverse inertia momentum in flight by larger hip flexion-abduction, which proportionally increased the angular velocities of their bodies. Their greater backward rotation angles at release were compensated by longer flight durations and increase angular velocity due to more reduced moments of inertia. This accounts for the greater forward rotation angle at regrasp for a total rotation of 140° in flight. The higher measured values of the minimal moment of inertia in flight for the novice group could be due to their larger hip extension velocities at release. In fact, the optimal technique (Huchez, Haering, Holvoët, Barbier, & Begon, 2015) displayed transfer the angular momentum of lower limbs to the rest of the body by a strong hip flexion in the first part of the aerial phase. Gymnasts of novice group have to achieve a greater deceleration of the hip extension prior to bending the hips with less time in flight. This prevents them from optimally increasing their forward rotation by reducing their moments of inertia. Because both the release state and the minimal moment of inertia in flight differed between the two groups, future studies should investigate which of these parameters more significantly maximises the body rotation.

The release angle is an important factor affecting the connection success. A more vertically oriented release velocity allows the gymnast to increase flight time and, consequently, the forward rotation by the conservation of angular momentum in flight. Theoretically, this increase has an asymptotic value and is a function of the anthropometry of the gymnast. In effect, a horizontal component of the release velocity is required for forward travel and to be able to grasp the high bar. The failure of the novice gymnasts to perform the connection, with a rotation angle at regrasp two to three times lower than that of expert group, confirms that that a high rotation angle at regrasp is a guarantee for a successful connection (Gervais & Tally, 1993).

What makes the counter movement forward in flight high demanding for novice gymnasts are the short flight duration (0.44 s versus 0.80 to 0.92 in Jaeger, Gaylord or Pegan; Brüggeman et al., 1994; Cuk, 1995; Gervais & Tally, 1993) and the large angular momentum (up to 10 times higher than during the Tkatchev: 2.19 rev/s versus 0.22 rev/s in outward Tkatchev; Kerwin & Irwin, 2010).

Implications for Learning and Safety

Novice gymnasts did not show a higher variability than expert gymnasts in the release state, indicating that the preparatory underswing is a robust technique for novices (*i.e.,* a movement they are able to perform with consistency). However, this may be an obstacle towards the learning process of their training. The practice and use of the underswing dismount (Figure 2) during the early stages of their training may have a negative effect (termed “negative transfer”; Schmidt & Lee, 1999) on the counter movement forward in flight progression. Therefore, this technique should not be viewed as a pre-requisite in the learning progression.

The novice gymnasts may not achieve the appropriate release parameters because they favour a technique that minimises the chances and consequences of failure. Generally, when a gymnast fails a release and regrasp element, she falls on the bar or onto the mat. Thus, athletes have to develop techniques for reducing risks or minimising failure consequences. For example, in Kerwin and Irwin’s study (2010), the risk of striking the low bar when failing a Tkachev led gymnasts to proceed at a lower velocity and angular momentum in the outward technique compared with the inward technique. In the counter movement forward in flight, the novice gymnasts had a short aerial phase and a large moment of inertia. This combination ensured a safe landing if they missed regrasping the bar. Because the counter movement forward in flight is among the first release and regrasp elements performed by novice gymnasts, their technique considerably reduced the failure consequences. Moreover, the increased horizontal velocity at release maximised the chance of catching the bar at the expense of body rotation.

Similarly, the expert technique reduced failure consequences. In elements with a forward rotation at regrasp, a body rotation angle of approximately 45° (Gervais & Tally 1993, see Figure 1) allowed the gymnast to fall flat on the mat in the case of failure. A greater angle would increase the swing potential but would also increase the risk of injury due to an over-rotated landing on the mat. In this case, the most suitable technique for success and connection is not the safest. That can explain why in spite of differences in the techniques they used, both groups, and not only the novice one, adopted a strategy reducing the failure consequences.

LIMITATIONS

Four limitations of the present study need to be acknowledged. First, due to experimental constraints such as marker occlusions by chalk use, only a limited number of trials could be analysed. Second, though expert group was composed of national-level gymnasts, individual techniques could still be improved by maximising the regrasp angle (Huchez et al., 2015) and consistency criteria (e.g., Hiley & Yeadon, 2003; 2012). Nevertheless, measured parameters showed significant differences between the groups in the current study. Third, for future study, body height and body weight matched control should be recruited, to eliminate their potential effect on movement performance. Fourth, the results of this study highlighted differences between expert and novice gymnasts performing the same skill, but did not investigate how the coordination pattern of novice gymnasts could evolve towards that of expert gymnasts. To this end, future studies should assess phase lags involved when gymnasts with different expertise levels perform a counter movement forward in flight. Such issues could be investigated through training studies with multiple testing sessions.

Recommendations for coaches and judges

The differences found between novice and expert gymnasts performing the counter movement forward in flight can be useful for coaches and judges. Coaches could help novice gymnasts to decrease their dependency on the described robust technique by improving the release angle. Exercises in which gymnasts land in a seated posture on an increasingly taller pile of mats and instructions such as to aim for the high bar with their feet could be used. They could allow novice gymnasts to exceed the threshold of a 90° rotation angle at release. Indeed, the rotation angle at release was significantly higher in the expert group and quite systematically greater than 90° (only three trials were inferior to 90°). Releasing the low bar with a rotation angle greater than 90° would result in a more upward hip extension and consequently in a more vertically oriented release velocity. To allow a successful connection, such an improvement of the release angle should be accompanied by a progress in the reduction of the moment of inertia in flight.

Though expert gymnasts were able to link the two elements, they received the same deduction by judges as novice gymnasts because they regrasped the high bar when their shoulders were below the bar and their ankles were ahead of the horizontal position of the shoulders. Because the shoulders could be above the bar at a low regrasp angle, this parameter is not directly related to the swing potential and therefore to a smooth connection between the elements. Based on our mechanical analysis, the scoring guide should instead require a 45° rotation angle at regrasp with graduated deductions as the regrasp angle approaches the vertical.

CONCLUSION

The release angle and the rotation angle at release are key mechanical parameters to increase success of the counter movement forward in flight performed in combination with a kip to support. Expert gymnasts performed better than novice gymnasts because they released the low bar higher (their centre of mass above the horizontal) and with a larger vertical velocity. They also had a smaller minimum moment of inertia in flight and spent more time in flight.

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