PREPRINT: Motor variability regulation analysis in trampolinists

Mathieu Bourgeois [1, †], Eve Charbonneau [1, †], Craig Turner [1] and Mickaël Begon [1]

[1] *Laboratoire de Simulation et Modélisation du Mouvement, Université de Montréal, Montréal, QC, Canada*

[†] *The two first authors have contributed equally to this study*

mathieu.bourgeois@gmail.com

eve.charbonneau.1@umontreal.ca

craig.turner@umontreal.ca

mickael.begon@umontreal.ca

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Abstract

In trampolining, optimizing body orientation during landing reduces injury risk and enhances performance. As athletes are subject to motor variability, anticipatory inflight corrections are necessary to regulate their body orientation before landing. This study first investigated the evolution of body orientation and limb position variability during twisting somersaults of various difficulties. A secondary objective was to examine the link between acrobatics difficulty and the variability accumulation and to identify links between body orientation variability and gaze orientation. Kinematics and gaze orientation were captured using inertial measurement units and a portable eye tracker, respectively. Seventeen trampolinists performed up to 13 different acrobatics. Pelvis orientation and limb positions inter-trial variability was computed at three key timestamps: take-off, 75% completion of the twist for the most twisting somersault, and landing. Pelvis orientation variability significantly increased (+75%) and then decreased (-39%) while there was an opposite pattern for the limbs where variability decreased (upper limbs: -66% and lower limbs: -46%) and increased (+357% and +127%), suggesting that trampolinists adapted their limb kinematics to regulate pelvis orientation before landing. A decreased body orientation variability was observed when athletes looked at the trampoline bed before landing. Thus, coaches should ensure that the acrobatic technique allows for getting the appropriate visual information to facilitate landings. Moreover, there was a moderate correlation between the number of twists in a straight somersault and the variability accumulation at 75% of the twist, highlighting that athletes accumulate more variability as the number of twist rotations increases.

Keywords: variability regulation; motor control; sensory acquisition; aerial acrobatics; twisting somersaults

Introduction

Bernshteĭn (1967) emphasized that although athletes repeat the same skills over and over, they do not produce strictly identical kinematics: "Practice is a particular type of repetition without repetition". Omnipresent in human movements, variability was long perceived as noise originating from the central nervous system and often considered detrimental to performance (Newell & Corcos, 1993). The Nonlinear Dynamical Systems Theory (Bernshteĭn, 1967; Kelso, 1995) has provided a new perspective on motor variability, no longer viewed as undesirable but as <u>functional</u> since it allows for injury risk reduction and performance improvement (Bartlett et al., 2007; Hiley et al., 2013; Preatoni et al., 2013). Cowin et al. (2022) categorized motor variability into three types: <u>strategic</u> (different ways a task can be accomplished, voluntarily or involuntarily), <u>execution</u> (different kinematic patterns used voluntarily or involuntarily to perform a task within the same strategy), and <u>outcome</u> (different performances observed due to the system's adaptation failure, which occurs involuntarily) variabilities. As similar sports performance can be achieved through various kinematics due to the musculoskeletal system redundancy (Bartlett et al., 2007; Sayyah et al., 2018), low outcome variability does not necessarily imply low execution variability. This redundancy allows for error compensation and constraint adaptations while maintaining performance outcomes (Bartlett et al., 2007). According to the minimum intervention principle proposed by Todorov (2004), the central nervous system would focus on regulating outcome variability and not execution variability, correcting only the motor variability detrimental to the task. This principle is highlighted by athletes' movements becoming more variable with expertise, as they improve at adapting to different execution conditions by deviating from the originally planned movement, correcting only detrimental components (Wilson et al., 2008). Thus, analyzing human motor variability can deepen our understanding of human movement control by providing insights into which movement components are necessary for consistent performance.

In trampolining, a key performance component is landing in an appropriate posture to initiate the next acrobatics of the sequence. As the angular momentum is preserved in free fall, athletes continuously modify their moment of inertia through limb movements to adjust their body angular velocity and achieve this appropriate landing orientation (Yeadon, 1993). These continuous adaptations during complex movements involving fast rotations on multiple axes would indicate the use of various motor control strategies (open-loop, feedback, and feedforward control), as discussed in the literature on gymnastics (Bardy & Laurent, 1998) and diving (Sayyah et al., 2018). First, open-loop control involves executing a pre-planned motor program chosen based on experience, without preparing for future adjustments. Experimental data contradict the continuous use of this strategy throughout acrobatics, as athletes were observed making motor corrections (Bardy & Laurent, 1998; Lee et al., 1992; Sayyah et al., 2018). Additionally, the use of sensory acquisition strategies like 'spotting' (Heinen, 2011), where athletes slow down their head angular velocity, suggests that athletes may use sensory information to make corrections during acrobatics, arguing against the sole use of open-loop control. Second, closed-loop feedback control involves making motor corrections based on a mismatch between the expected and actual sensory information whether visual, vestibular, or proprioceptive. Third, feedforward control relies on an internal forward model to anticipate the motor outcome of the movement and make prospective motor corrections to the ongoing movement to achieve the goal (Sayyah et al., 2018). This strategy was observed during backward somersaults, where gymnasts made corrections based on their estimation of the remaining distance and time left before landing (Bardy & Laurent, 1998). In trampolining, movement regulation is thought to be driven by vision since trampolinists use the trampoline as a reference point to guide their acrobatics (Heinen, 2011; Natrup et al., 2020, 2021). However, due to the body rotations involved in acrobatics, it is not always possible to see the trampoline, possibly making acrobatic regulation based on visual information harder. If this is the case, variability can be expected to accumulate during these phases where the trampoline is not visible. Previous studies have examined either the sensory acquisition behavior (Heinen, 2011; Natrup et al., 2020, 2021; Charbonneau et al., 2023) or the execution variability of acrobatic athletes (Bardy & Laurent, 1998; Sayyah et al., 2018), but no study explicitly linked them together. Understanding the perception-action mechanisms responsible for corrections of motor execution using sensory information might help coaches prescribe trampolining techniques that are more easily adaptable.

The primary objective of this study was to assess the execution variability of trampolinists during acrobatics, with a particular focus on the pelvis orientation and lib positions. Additionally, we aimed to examine the link between acrobatics difficulty and variability accumulation. Lastly, an exploratory objective was to investigate if trampolinists regulate pelvis orientation variability using visual information when looking at the trampoline bed. In line with previous research (Bardy & Laurent, 1998; Sayyah et al., 2018), we hypothesized that the variability in pelvis orientation increases after takeoff, and decreases before landing. Since changes in body orientation are regulated using limb movements through angular momentum conservation, we hypothesized that the limb variability increases before landing. This regulation might be more challenging when the difficulty of the acrobatic increases, thus we expected the body orientation variability to increase with the acrobatic difficulty. Finally, we hypothesized that the variability increase-decrease switches happen when the athletes start seeing the trampoline.

Methods

Data collection

Eight elite (4♀/4♂; 22.3±4.7 years) and nine sub-elite (6♀/3♂; 15.3±2.7 years) trampolinists participated in this study. The data collection is described in detail in Charbonneau et al. (2023). The experimental protocol (No. CERC-19-002-D) was approved by the Université de Montréal Research Ethics Committee. The participants (and their guardians for minors) provided written informed consent to participate in the study.

The athletes' gaze orientation was measured at 200 Hz using a wearable eye-tracking device (Pupil Invisible, Pupil Labs, Germany). Whole body kinematics were measured at 60 Hz using 17 inertial measurement units (IMUs; Xsens MTw, Movella Inc., United States) placed on the athletes' limbs following the manufacturer's instructions (Fig. 1). Measurement tools were synchronized offline by optimizing the time alignment of the touchdown and takeoff timestamps of the preparatory jumps as explained in Charbonneau et al. (2023).

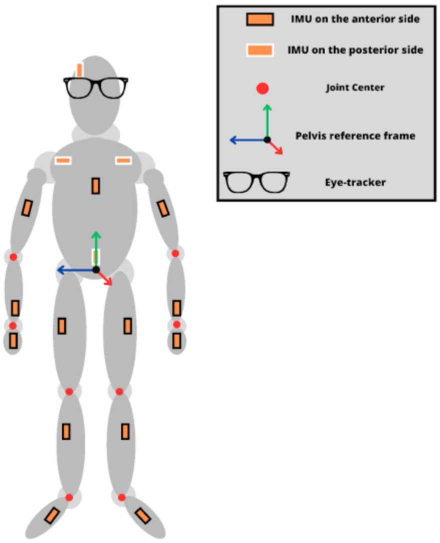

Figure 1: Placement of the measuring equipment (IMUs and eye tracker), along with the joint centers considered during analysis and the pelvis reference frame in which they are expressed.

Participants warmed up freely for 5-15 minutes while equipped with the measurement devices for acclimation. All athletes performed six simple acrobatics on a trampoline in a randomized order, and elite athletes executed up to seven more complex acrobatics (Tab. 1). The acrobatics were paired two-by-two and repeated to compose 10-acrobatics sequences (alternating forward and backward movements without constraint on the choice of acrobatics) to match the competition requirements. Any acrobatics that did not land on the trampoline bed failed to meet the correct number of somersaults or twists, and those affected by a malfunction of any acquisition systems were discarded.

Table 1: The number of trials for each of the 13 acrobatics and their characteristics: direction of somersault rotation, body posture, number of somersaults and twists

Acrobatics FIG Code	Rotation direction	Body posture	Number of somersaults	Number of twists		Number of trials	Number of athletes
				First somersault	Second somersault		
4-/	Back	Straight	1	0	/	190	17
4-o	Back	Tuck	1	0	/	272	15
41/	Front	Straight	1	0.5	/	185	17
41o	Front	Tuck	1	0.5	/	240	15
42/	Back	Straight	1	1	/	163	17
43/	Front	Straight	1	1.5	/	153	15
8- -o	Back	Tuck	2	0	0	41	8
8-1<	Front	Pike	2	0	0.5	35	5
8-1o	Front	Tuck	2	0	0.5	58	8
811<	Back	Pike	2	0.5	0.5	25	5
8-3<	Front	Pike	2	0	1.5	33	7
831<	Back	Pike	2	1.5	0.5	15	4
822/	Back	Straight	2	1	1	13	4

Kinematics variability and analysis

The body orientation was defined as the pelvis Euler angles (somersault, tilt, and twist) extracted from the pelvis quaternions given by the MVN Analyze software (Schepers et al., 2018). The upper limb (elbow and wrist) and lower limb (knee and ankle) joint centers expressed in the pelvis reference frame were extracted from the kinematics provided by the same software. To represent the gaze orientation in the gymnasium reference frame, the eye angles were connected to the body kinematics, allowing retrieval of the temporal evolution of the gaze orientation endpoint towards the trampoline and the gymnasium floor (Charbonneau et al., 2023). Each acrobatics aerial phase was time normalized (from 0% to 100%) to compute the motor variability across trials of the same acrobatic for each athlete. The pelvis orientation and limb position variabilities were computed as the standard deviation of the pelvis angles and joint center positions (Grassi et al., 2005), respectively. To simplify the interpretation, the standard deviations on each of the three axes were summed to obtain a total standard deviation (SDtotal). For the joint center positions, the SDtotal values were also normalized according to the segment length for each subject. Furthermore, these normalized values were categorized into upper limbs (mean of left and right elbows and wrists) and lower limbs (mean of knees and ankles). For statistical analysis, we reported SDtotal at take-off (T_{TO}), 75% of twist completion during the most twisting somersault (T_{75}), and landing (T_{LA}). T_{75} was selected as we expected the variability to accumulate during the twist due to the difficulty of acquiring visual feedback when the head rotates fast. In the three acrobatics without twist (backward somersault in tuck and straight position and the double backward somersault in tuck position), T_{75} could not be calculated, therefore they were excluded from the variability comparisons. A Shapiro-Wilk test and a Levene's test showed the non-normality and heterogeneity of variances of SDtotal at T_{TO}, T_{75}, and T_{LA} was, thus non-parametric tests were used. A Kruskal-Wallis test was used to compare pelvis orientation and joint center position variability (*i.e.*, SDtotal) across the three different timestamps (T_{TO}, T_{75}, and T_{LA}), followed by a Dunn's post-hoc test with a Bonferroni correction applied for each timestamp (n=3). If the Kruskal-Wallis test was significant, the same investigations were carried out for each acrobatic independently. For each analysis, the *p*-value significance threshold was set to 0.05.

As athletes use the trampoline bed as a reference point in the foveal and peripheral vision (Charbonneau et al., 2023), the gaze-on-trampoline (trampoline in foveal vision) and gaze-on-gymnasium floor (trampoline in peripheral vision) timestamps were cross-referenced with pelvis orientation for visual representation and qualitative description. A descriptive analysis was preferred over a quantitative analysis to address our exploratory objective, due to the intermittent visibility of the trampoline during acrobatics making the choice of an appropriate metric challenging.

Since we considered the head rotation velocity as the limiting factor for visual information intake, we attributed a difficulty score based on the mean norm of the rotation rate vector obtained at T_{75} for each acrobatic move. The correlations between the rotation rate and the pelvis orientation SDtotal of all trials for each acrobatics were assessed using a Pearson linear correlation analysis. Since the difficulty score might not be representative of the perceptivo-motor complexity across acrobatics performed in different postures (tuck, pike, or straight), we performed the same correlation including only the most performed straight acrobatics (forward somersault with a ½ twist, backward somersault with a twist, and forward somersault with 1½ twists). In our interpretation, a coefficient determination of 0–0.10, 0.10–0.39, 0.40–0.69, 0.70–0.89, and 0.90–1.00 were considered negligible, weak, moderate, strong, and very strong, respectively (Schober et al., 2018). No statistical analysis was conducted on gaze orientation.

Results

A significant increase of +75% in the SDtotal pelvis orientation was observed between T_{TO} and T_{75} ($p<0.001$), followed by a significant decrease of -39% between T_{75} and T_{LA} ($p<0.001$; Fig. 2a). At T_{LA}, SDtotal returned to a value close to that observed at T_{TO} ($p>0.05$). The comparison for each acrobatic independently led to a similar increase-decrease pattern with a significant difference observed for 4 out of 10 acrobatics (Fig. 2b). For all acrobatics, no significant differences were observed between T_{TO} and T_{LA}, except for one acrobatic (forward somersault with 1½ twists), which showed a significant increase ($p=0.042$; Fig. 2b). This pattern was inverted for limb positions variability where the upper limb variability showed a significant decrease of -66% ($p<0.001$) between T_{TO}

and T_{75}, followed by a significant increase of +357% between T_{75} and T_{LA} ($p<0.001$; Fig. 2c). Similarly for the lower limbs, there was a significant variability decrease of -46% ($p<0.001$) from T_{TO} to T_{75}, followed by a significant increase of +127% between T_{75} and T_{LA} ($p<0.001$; Fig. 2e). In both cases, significant increases of 59% ($p<0.001$; Fig. 2c) and 21% ($p<0.01$; Fig. 2e) for the upper and lower body, respectively, between T_{TO} and T_{LA} were observed. The variability of the upper and lower limbs was also assessed for each acrobatic independently resulting in a similar pattern (Fig. 2d and Fig. 2f). The forward somersault with 1½ twists and the backward somersault with 1 twist showed a significant difference between T_{TO} and T_{LA} for lower limbs ($p=0.008$ and $p=0.019$ respectively; Fig. 2d). The forward somersault with 1½ twists also showed this difference for the upper limbs ($p=0.034$; Fig. 2f).

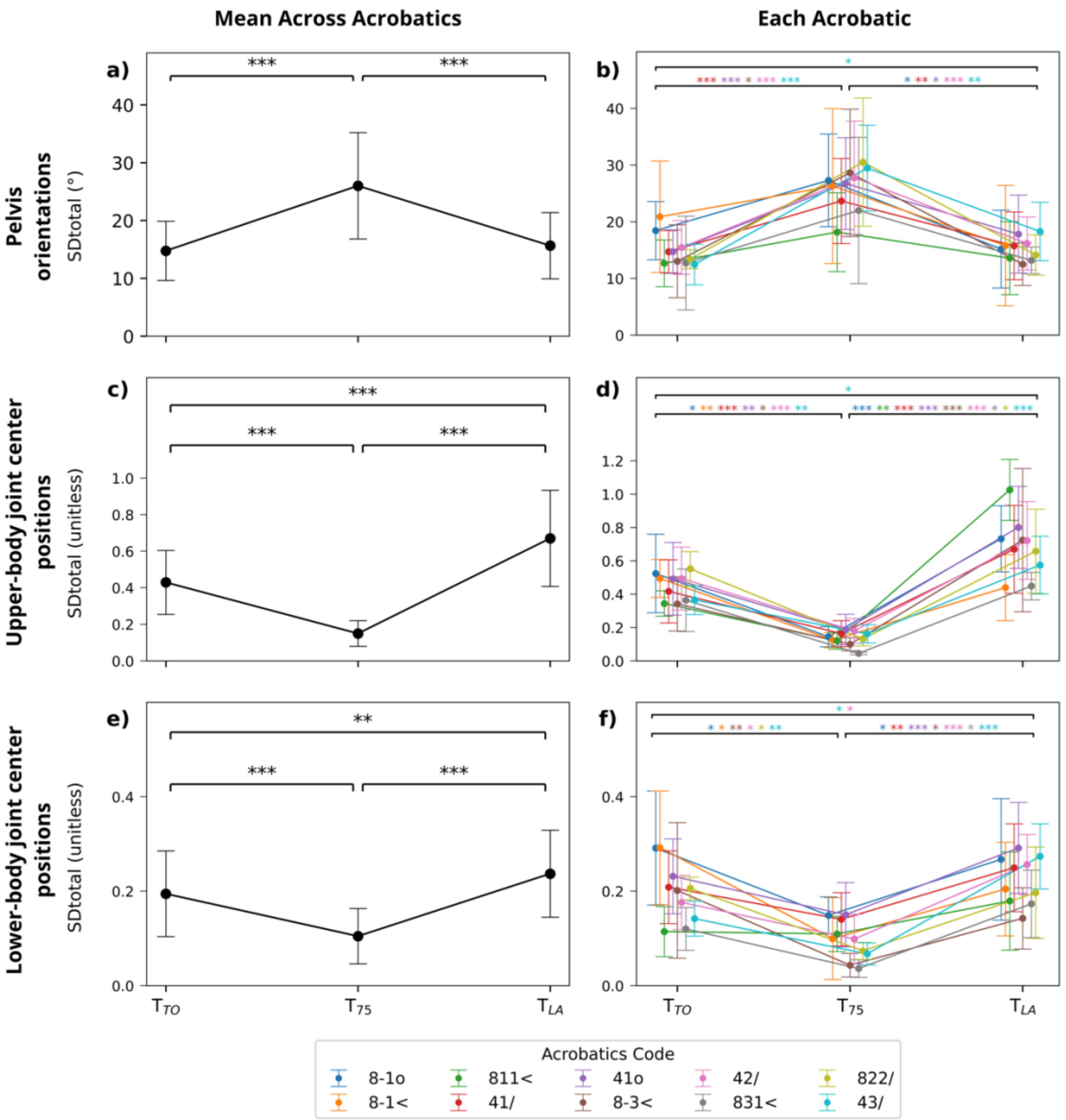

Figure 2: Sum of the standard deviation (SDtotal) at takeoff (T_{TO}), 75% completion of the twist rotation (T_{75}), and landing (T_{LA}) for pelvis orientations (a, b), the mean of upper (c, d) and lower limbs (e, f) joint center positions. The average across all trials for all acrobatics (left column) and the average across all trials for each acrobatic (right column) are shown. Significance levels are indicated as follows: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

No correlation was found between pelvis orientation variability at T_{75} and the acrobatics difficulty ratio (r=0.10; p=0.315; Fig. 3a). When only the single straight somersaults with ½, 1, and 1½ twists were included, there was a moderate correlation between the difficulty score and the variability at T_{75} (r=0.43; p=0.003; Fig. 3b). The SDtotal at T_{75} increased by about 19% for each additional ½ twist.

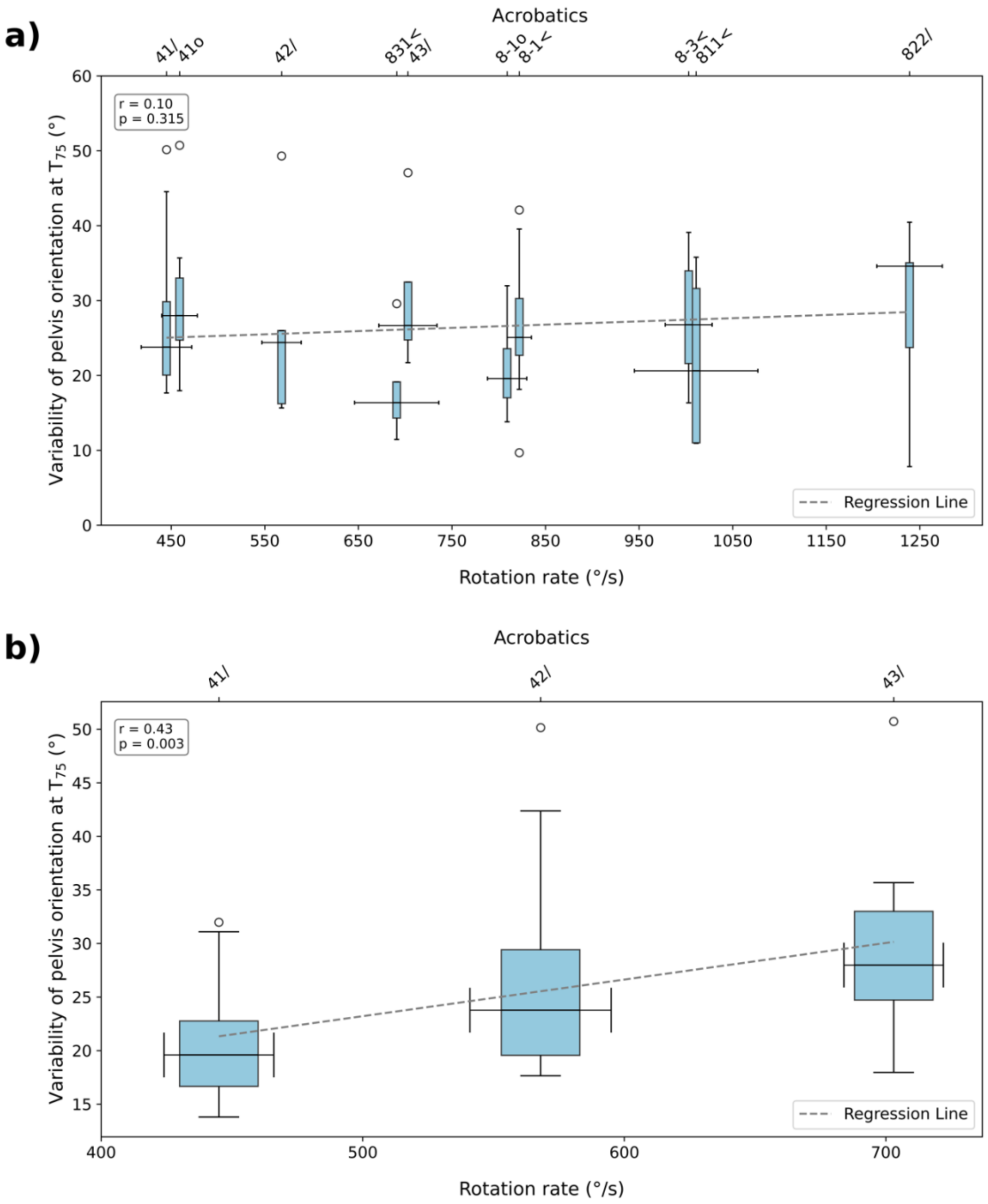

Figure 3: Boxplots illustrating the SDtotal of the pelvis orientation at T_{75} for a) all acrobatics and b) most commonly performed straight acrobatics according to their mean and standard deviation of the rotation rate norm.

Regardless of the acrobatics, athletes spent most of the time looking at the gymnasium floor and, more specifically, the trampoline bed, with similar timing amongst all subjects (Fig. 4 and Fig. 5). The beginning of the pelvis orientation variability decrease seems to coincide with the beginning of the gaze fixation on the gymnasium floor for most athletes and most acrobatics (Fig. 4 and Fig. 5).

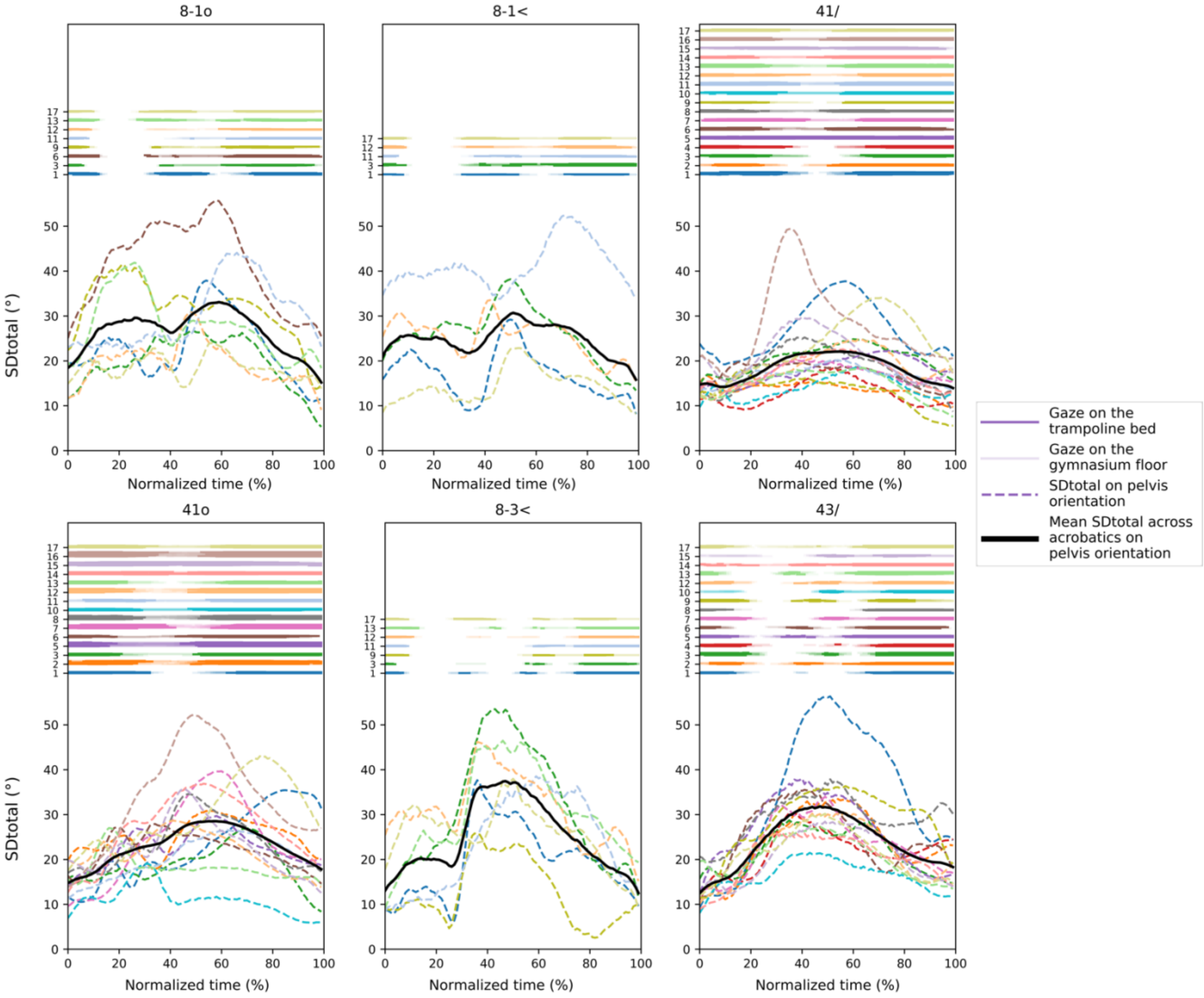

Figure 4: Time series of the sum of the standard deviation (SDtotal) of pelvis orientation for the forward acrobatics are presented in the lower part of the graphs. Timings, when the gaze is oriented toward the trampoline bed (solid line) and the gymnasium floor (transparent line), are presented in the upper part of the graphs. Each graph represents a different forward acrobatic and each color represents a different athlete.

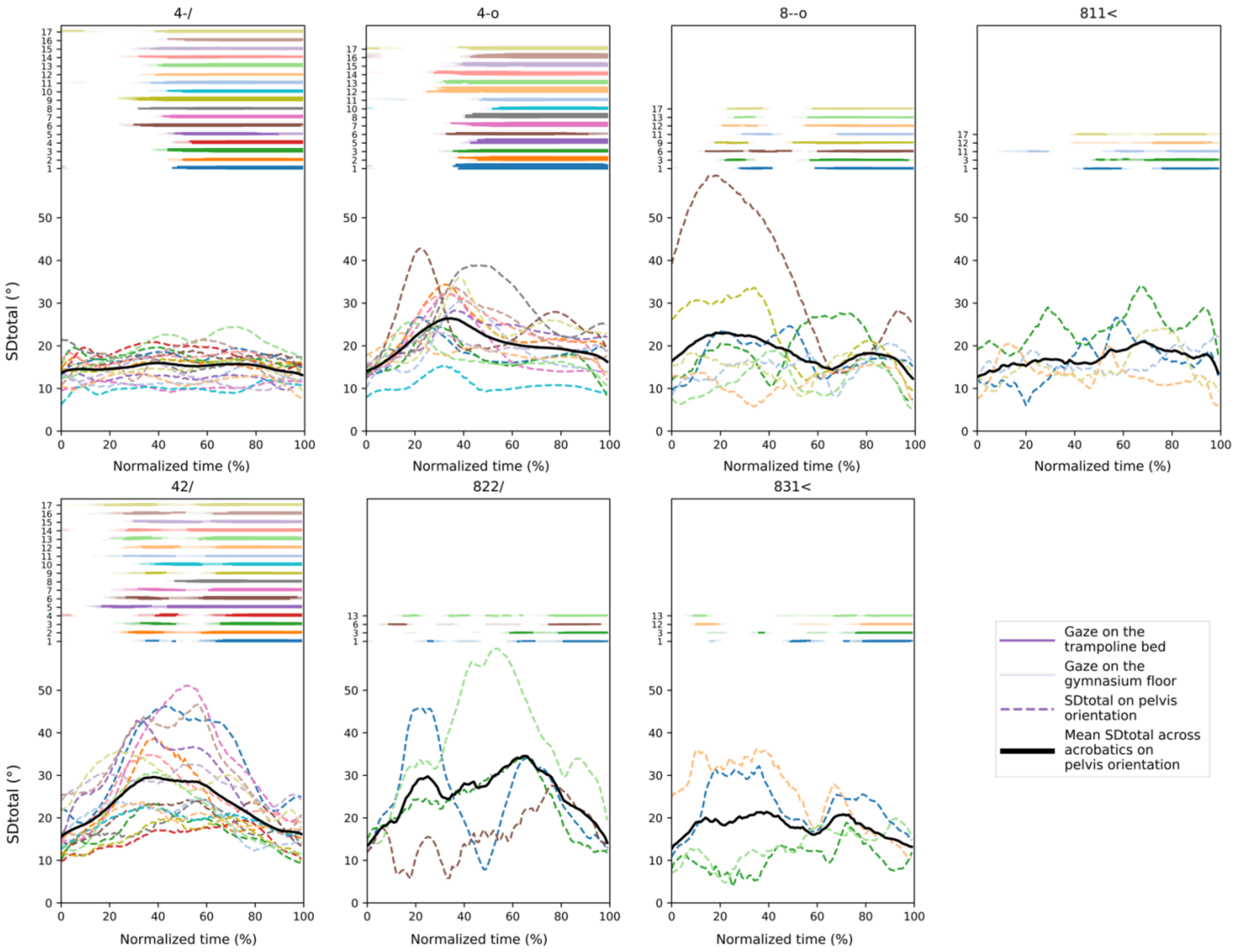

Figure 5: Time series of the sum of the standard deviation (SDtotal) of pelvis orientations for the backward acrobatics are presented in the lower part of the graphs. Timings, when the gaze is oriented toward the trampoline bed (solid line) and the gymnasium floor (transparent line), are presented in the upper part of the graphs. Each graph represents a different backward acrobatic and each color represents a different athlete.

Discussion

We assessed the motor regulation ability of trampolinists by measuring their execution variability during various acrobatics. In the first phase of the acrobatics (T_{TO} to T_{75}), pelvis orientation variability increased while limb variability decreased. In the last phase of the acrobatics (T_{75} to T_{LA}), the opposite pattern occurred with a decrease in pelvis orientation variability and an increase in limb variability. Although more complex acrobatics tended to accumulate greater variability at T_{75}, athletes still managed to regulate most of their pelvis orientation variability before landing with variability values like those at takeoff, except for the forward somersault with 1½ twists. Additionally, variability appeared to decrease when the trampolinists' gaze was directed at the trampoline bed, though this was inconsistent across all acrobatics.

Pelvis orientation variability increases after takeoff

Previous studies have shown that body orientation variability tends to accumulate during the first part of acrobatics during somersaults in gymnastics (Bardy & Laurent, 1998) and diving (Sayyah et al., 2018). However, these studies only analyzed planar acrobatics (somersaults without twists). In line with our hypothesis, we highlight, here, that the pelvis orientation variability also increased during the first phase of twisting somersaults (T_{TO} and T_{75}), likely due to variations in body angular velocity at takeoff (Sayyah et al., 2018). This may suggest that trampolinists use an open-loop control strategy during the first phase of their acrobatics for their body orientation. The simultaneous decrease in limb position variability could indicate that, during this phase of acrobatics, trampolinists focus on adhering as closely as possible to the aesthetics prescribed by the code of points through proprioceptive closed-loop feedback control of the limbs. Because the variability in takeoff conditions is large and limb position is constrained by the code of points during the acrobatics, there is little room for athletes to correct pelvis orientation variability during the first phase of acrobatics. Thus, to maximize execution scoring, athletes would favor limb position regulation over pelvis orientation regulation during the first phase of their acrobatics.

Pelvis orientation variability decreases before landing

Previous research has shown that both gymnasts (Bardy & Laurent, 1998) and divers (Sayyah et al., 2018) decrease their body orientation variability before water entry of forward pike dives and 2½ forward pike dives and before landing of backward tuck somersault, respectively. Our results agree with these studies; as hypothesized, trampolinists' pelvis orientation variability decreased when approaching the landing phase (T_{75} to T_{LA}), likely due to the importance of body orientation in preparation for the next acrobatic. As argued by Bardy & Laurent (1998) and Lee et al. (1992), the reduction in pelvis orientation variability observed at the end of the acrobatics suggests the use of either: 1) a prospective (*i.e.*, feedforward) control strategy that is based on an internal forward model or 2) a feedback control strategy that is based on a sensory reference. Both the internal model and the sensory reference would have been improved through acrobatic experience (Hiley et al., 2013). As argued by Sayyah et al. (2018), the most likely scenario involves a combination of open-loop, feedback, and feedforward strategies throughout the movement. Our results agree with Bardy & Laurent (1998) and Sayyah et al. (2018), who showed that regulation is achieved through limb movement while airborne, leading to increased limb variability. This increase in limb variability indicates that athletes focus less on the aesthetic execution of acrobatics and more on preparing for a balanced landing. Nevertheless, these corrections did not completely remove pelvis orientation variability, with a small residual pelvis orientation variability remaining at the end of all acrobatics. It is unclear whether it represents an outcome variability or a functional variability, particularly for the forward somersault with 1½ twists where the pelvis orientation variability was significantly larger at landing than at takeoff. This acrobatic might present a regulation challenge for athletes, explaining athletes' aversion toward it. Future studies should investigate acrobatic performance in challenging conditions like subsequent acrobatics or smaller aerial time to determine at what point trampolinists reach their movement regulation limits during complex acrobatics.

Relationship between variability and acrobatic difficulty

To our knowledge, no studies have analyzed the evolution of movement variability across multiple acrobatics of increasing difficulty levels. In Sayyah et al. (2018) a greater body orientation variability was observed in the 2½ forward somersault pike dive compared to the forward pike dive. We hypothesized that more complex acrobatics would yield more pelvis orientation variability. However, our results showed only a moderate correlation between acrobatic complexity and variability accumulation. This lack of correlation might be explained by an inappropriate choice of acrobatics difficulty score (body angular velocity norm at 75% of twist completion). The motor and perceptual-cognitive difficulty of acrobatics is hard to capture using a single metric, especially when acrobatics are executed in different body positions and with different twist timing (twists in the first *vs* second somersault) as the motor and sensory demands vary. Therefore, further studies are necessary to uncover valuable insights into which factors make an acrobatic complex to regulate. To overcome this challenge, we focused on three straight acrobatics with ½, 1, and 1 ½ twists, and observed a significant moderate correlation. This correlation could be attributed to the increased rotational speed, which inherently heightens variability due to larger changes in pelvis orientation, making the gathering of sensory information for regulation more challenging. Thus, coaches should be cautious when teaching acrobatics with lots of twists, since more variability should be overcome to reach a safe landing.

The link between vision and variability regulation

On the one hand, biomechanical studies focused on measuring variability regulation during acrobatics such as flic-flac (Grassi et al., 2005), long swings on the high bar (Busquets et al., 2016; Hiley et al., 2013), and diving (Sayyah et al., 2018). On the other hand, neuroscience research has measured the importance of vision during double backward somersaults on a trampoline (Hondzinski & Darling, 2001) and backward somersaults on the floor (Luis & Tremblay, 2008). However, these two fields have only been remotely connected so far although Yeadon and Pain (2023) argued that motor control aspects should be considered in the analysis of sports kinematics to gain a deeper understanding of why elite athletes choose specific techniques. In this vein, Bardy & Laurent (1998) demonstrated the importance of visual acquisition in variability regulation during the back somersault on the floor. We hypothesized that this link between vision and variability extends to twisting somersaults on the trampoline, such that that visual information about the trampoline position is used to regulate body orientation variability. Our observations suggest a potential alignment with this hypothesis as the timing of pelvis orientation variability decrease appears to coincide with the beginning of the last fixation on the trampoline, although inconsistent across acrobatics. This could indicate that vision is used to regulate body orientation, but that other sensory information might also be used like vestibular, or proprioceptive feedback for the regulation of body orientation variability. Modifying the sensory information available to the athletes, for example, by limiting visual acquisition during certain phases of the movement (Davlin et al., 2001), using galvanic vestibular stimulation to perturb vestibular information (Fitzpatrick & Day, 2004), or using stroboscopic lights to remove image motion information (Rézette & Amblard, 1985), could provide a deeper understanding of the various regulation strategies used at each stage of acrobatics. In summary, our qualitative analysis suggests a trend where athletes would be able to decrease pelvis orientation variability when visual feedback is available, however, further investigations are needed to understand the sensorimotor mechanisms by which athletes regulate their acrobatics.

Limitations

The current study had two noteworthy limitations. First, the T_{TO} and T_{LA} timings were identified by optimizing the alignment of manual timestamps with IMU acceleration profiles, which might have led to small overestimations of variability when the timestamps were not perfectly identified. Second, to accommodate trampolinists' practice and performance conditions, each participant was permitted to perform all acrobatics at their preferred height; differences in flight time may have affected acrobatic regulation strategies, potentially impacting variability metrics.

Conclusion

During the first phase of their acrobatics, trampolinists focused on executing their acrobatics according to the code of points (*i.e.*, body alignment with straight arms and legs), which decreased their limb variability and increased their body orientation variability. Then, their focus switches to regulating body orientation before landing, making adjustments with their limbs. This strategy shift may indicate that athletes smoothly transition from open-loop control of the pelvis orientation and feedback control of the limb positions to maximize scoring into a combined feedback and feedforward control of the body orientation to optimize landing conditions. Thus, coaches should ensure that the athletes' technique allows for acquiring sensory information long before landing and that the arm kinematics is not constrained to enable adjustments of pelvis orientation using upper limb movements.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Contributions

Mathieu Bourgeois: Conceptualization, Data curation, Formal analysis, Software, Visualization, Writing - original draft

Eve Charbonneau: Conceptualization, Funding acquisition, Investigation, Methodology, Software, Writing - original draft

Craig Turner: Conceptualization, Writing - review & editing

Mickaël Begon: Conceptualization, Funding acquisition, Resources, Supervision, Writing - review & editing

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