# PREPRINT: Including visual criteria into predictive simulation of acrobatics to enhance the realism of optimal techniques.

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## Abstract

To perform their acrobatics successfully, trampolinists make real-time corrections mainly based on visual feedback. Despite athletes' heavy reliance on visual cues, visual criteria have not been introduced into predictive simulations yet. We aimed to introduce visual criteria into predictive simulations of the backward somersault with a twist and the double backward somersault with two twists in pike position to generate innovative and safe optimal acrobatic techniques. Different visual *vs* kinematics objective weightings were tested to find a good compromise. Four international coaches and two international judges assessed animations of the optimal techniques and of an elite athletes technique, providing insights into the acceptability of the optimal techniques. For the most complex acrobatics, coaches found the optimal techniques more efficient for aerial twist creation. However, they perceived them as less safe, less realistic, similarly aesthetic, and similarly appropriate for visual information intake compared with the athlete's technique. The scores given by the judges were twice as high for the optimal technique compared to the athlete's technique. This study highlights the importance of including visual criteria into the optimization of acrobatics to improve the relevance of the optimal techniques for the sporting community.

**Keywords – Gaze, Optimal control, Trampoline, Motor control, Visuo-motor strategies, Perception-action coupling**

# 1 Introduction

Biomechanics researchers have used predictive simulations to assist coaches through analysis and synthesis of sporting techniques [1, 2, 3]. However, previous optimal sporting techniques focused on the motor task, neglecting the crucial role of visual feedback during movement execution. Evidence from various sports, including table tennis [4], basketball [5], and running [6], suggests that athletes often prioritize visual information acquisition over biomechanically optimal movements when movement regulation is key to an increased performance. This is often presented in the form of eye/head stabilization. Some characteristics of the trampolinist kinematics point toward this prioritization, like spotting [7, 8], a strategy where the head is slowed down to increase sensory information acuity. It is expected that athletes choose acrobatic techniques where their head is oriented such that they are able to see informative portions of the environment, as vision plays an important role in spatial orientation [9]. Indeed, using a portable eye-tracker and inertial measurement units (IMUs), it was observed that trampolinists exhibit a characteristic series of visual behaviors during the execution of acrobatics [8, 10, 11]. One of them is looking at the trampoline bed at key instants of the acrobatics. Some athletes are conscious of this behavior and report making *visual contact* with precise portions of the trampoline to guide their acrobatics. Due to the athlete's rotation in the air, the head is not always positioned appropriately to see these *visual contact* points. As athletes are in free fall, the body orientation is dependant on the limb movements, thus the whole body kinematics might be modified to appropriately position the head. As athletes may prefer performing acrobatic techniques rich in *visual contact* points, facilitating the acrobatic execution control which is crucial to land safely, the motor and sensory aspects of acrobatic techniques cannot be considered independently. Thus, if we want to generate relevant acrobatic techniques, both the performance outcomes and the visual information intake should be maximized by optimizing simultaneously the gaze and body kinematics.

The gaze and body kinematics have previously been optimized simultaneously in predictive simulations of gaze shift [12]. It was established that the neck and eye movements follow the "principle of least effort", meaning that gaze orientation can be studied using the optimal control theory. However, the optimal gaze movements were only generated for simple head-eye movements; hence, it would be useful to push it further by generating optimal body-head-eye movements during acrobatics.

The primary aim of this study was to generate safer optimal acrobatic kinematics by including visual optimality criteria in the predictive simulations. The optimal kinematics generated with and without the visual criteria were compared in terms of twist creation, safety, realism, aesthetics, visual information intake, and execution. We hypothesized that integrating visual criteria into the predictive simulations would generate kinematics that are more similar to the technique used by athletes, thus increasing the acceptability of the proposed optimal techniques.

# 2 Methods

## 2.1 Experimental procedure

The kinematics and gaze orientation of one elite female trampolinist in the top 10 worldwide (Tier 5 according to the Participant Classification Framework [13]) were measured using 17 inertial measurement units (MTw, Xsens Technologies B. V., Netherlands) and a wearable eye tracking device (Pupil Invisible, Pupil Labs, Germany). The protocol (No. CERC-19-002-D) was approved by the Université de Montréal Research Ethics Committee, and the participant provided verbal and written informed consent to participate. The acrobatics in this study are the backward somersault in straight position with one twist (acrobatic code: 42/) and the double backward somersault in pike position including 1½ twists in the first somersault and ½ twist in the second somersault (acrobatic code: 831<). The athlete performed the acrobatics within one hour of trampoline practice including recovery breaks to avoid fatigue. Five repetition of the backward somersault in straight position with one twist and four repetitions of the double backward somersault in pike position including two twists were retained in this study for further analysis. The data were acquired and processed as described in [8] to generate body and eye animations of the athlete's technique.

## 2.2 Predictive simulation

A model composed of 20 degrees of freedom (Fig. 1a) was personalized using the athlete's segment inertial parameters in line with the Yeadon anthropometric model [14]. The visual field was modeled using a 45° vision cone (Fig. 1b) discretized into 100 vectors. The vector distribution densifies as we approach the center of the cone. The model was controlled by joint accelerations ($\ddot{q}_j$) using the free-fall multibody dynamics [15].

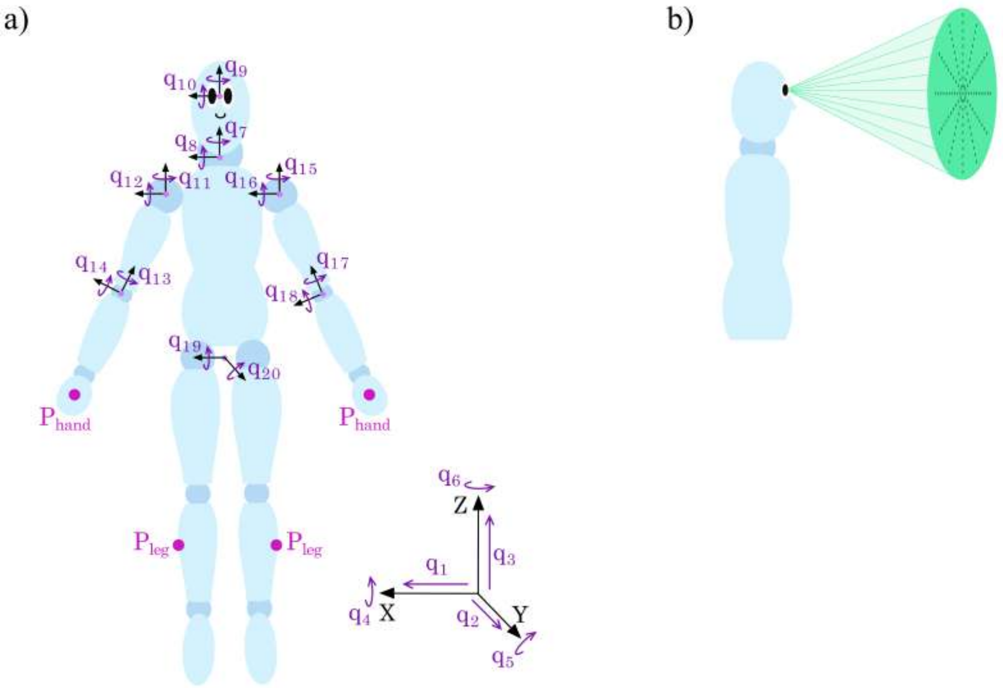

Figure 1. Front (a) and side (b) views of the model composed of 20 degrees of freedom (six at the trunk, which acts as the root segment, two at each shoulder, two at each elbow, two at the hips, two at the neck, and two at the eyes), four markers for the pike constraint (one on each lower leg ($P_{leg}$) and each hand ($P_{hand}$)), and a vision cone.

Optimal kinematics for both acrobatics were generated by solving an optimal control problem (OCP) in Bioptim [16] using a multiple shooting transcription with a $4^{th}$ order Runge-Kuta integrator and the solver IPOPT [17]. The backward somersault with one twist was composed of two phases of free duration: *i)* twisting phase and *ii)* preparation for landing. The double backward somersault with two twists in pike position was composed of six phases of free duration: *i)* twisting phase, *ii)* reaching the pike position, *iii)* somersaulting in pike position, *iv)* hip extension (kick-out), *v)* half twist, and *vi)* preparation for landing. The constraints were to join the hands ($P_{hand}$) and legs ($P_{leg}$) during the pike position (Fig. 1) and to complete the acrobatic within the same duration as the athlete's performance. The model took off from the trampoline center in a straight position with only vertical and somersault velocities (without tilt and twist velocities), meaning only aerial twisting was possible. The cost function comprised kinematic objectives to ensure conformity with the sports regulations [18] and visual objectives to ensure the accessibility of visual information (Tab. 1). The kinematic objectives consisted of minimizing the joint angles, joint accelerations, joint jerks, and the duration of some phases. The visual objectives were chosen based on our previous experimental work [8], where we observed that athletes used a predefined sequence of visuomotor strategies during their acrobatics: spotting (*i.e.*, slowing down the head angular velocity in the gymnasium reference frame), blinking, self-motion detection (*i.e.*, keeping the eyes still in the head reference frame during fast rotations of the head), anticipatory movements (*i.e.*, eye-head synergistic movements either aiming to reposition the gaze or to compensate for the body's rotation in space), looking at the trampoline bed, and fixation on the trampoline bed before landing. Here, we introduce the following objective terms (see Appendix A for more details) to reflect these visual behaviors:

**Spotting:** Minimization of the angular velocity of the head in the global reference frame ($\mathbf{V^2_{head}}$).

**Self-motion detection:** Minimization of the angular velocity of the eyes in the head reference frame ($\mathbf{\dot{q}^2_{eyes}}$).

**Anticipatory movements:** Minimisation of the extreme eye and head angles to encourage synergies ($\mathbf{q^2_{eyes}} + \mathbf{q^2_{head}}$)

**Looking at the trampoline:** Maximizing the intersection area between the vision cone and the trampoline bed (xOy plane). This was done by gradually penalizing each vector from the discretized vision cone falling outside of the trampoline bed
$(\mathbf{tanh}((\frac{\mathbf{gaze_x}}{\mathbf{trampoline\ width}}^{\mathbf{6}} + \frac{\mathbf{gaze_y}}{\mathbf{trampoline\ length}}^{\mathbf{6}}) - \mathbf{1}) + \mathbf{1})$

**Fixation on the trampoline:** Minimizing the difference between the gaze vector and the vector jointing the eyes to the fixation target positioned 1.07 m forward from the center, which corresponds to the horizontal red line on the front part of the trampoline bed
$(\mathbf{arctan}(\|\overrightarrow{\mathbf{gaze}} \times \overrightarrow{\mathbf{fixation}}\| / \overrightarrow{\mathbf{gaze}} \cdot \overrightarrow{\mathbf{fixation}}))$

Blinking was not modeled as it should not have an impact on the optimal kinematics.

Table 1. Weights of the objective terms added to the cost function for the backward somersault with one twist (42/: top) and the double backward somersault with two twists in pike position (831<: bottom) at each phase

| | 42/ | Mathematical expression | Phase #1<br>Twisting | Phase #2<br>Landing |
|---|---|---|---|---|
| Kinematics | Min joint acceleration | $\ddot{q}^2$ | 1 | 1 |
| | Min joint jerk | $(\Delta\ddot{q})^2$ | 1 | 1 |
| | Min phase time | $t_i^2$ | 0.00001 | 0.00001 |
| | Arms along the body | $q_{shoulder}^2$ | 50 000 | |
| | Min tilt | $q_{tilt}^2$ | | end: 1 000 |
| Vision | Spotting | $V_{head}^2$ | 10 | |
| | Self-motion detection | $\dot{q}_{eye}^2$ | 1 | |
| | Extreme eye angles | $q_{eye}^2$ | 10 | 10 |
| | Extreme neck angles | $q_{head}^2$ | 100 | 100 |
| | Look at the trampoline | $\tanh((\frac{Gx}{Tx}^6+\frac{Gy}{Ty}^6)-1)+1)$ | 100 | |
| | Fixation on the trampoline | $\arctan((\lVert\vec{G}\times\vec{F}\rVert / \vec{G}\cdot\vec{F}))$ | 1 | 1 000 |

$$\times \begin{bmatrix}0\\0.25\\0.5\\0.75\\1\\1.25\\1.5\\1.75\\2\end{bmatrix}$$

Notation:

$G_X$ = $gaze_X$
$G_Y$ = $gaze_Y$
$T_X$ = trampoline width
$T_Y$ = trampoline length
G = gaze
F = fixation

| | 831< | Mathematical expression | Phase #1<br>Twisting | Phase #2<br>Piking | Phase #3<br>Somersault | Phase #4<br>Kick-out | Phase #5<br>½ twist | Phase #6<br>Landing |
|---|---|---|---|---|---|---|---|---|
| Kinematics | Min joint acceleration | $\ddot{q}^2$ | 1 | 1 | 1 | 1 | 1 | 1 |
| | Min joint jerk | $(\Delta\ddot{q})^2$ | 1 | 1 | 1 | 1 | 1 | 1 |
| | Min phase time | $t_i^2$ | 1 | 100 | -0.01 | 100 | -0.01 | -0.01 |
| | Encourage piking | $(P_{hand} - P_{leg})^2$ | | end: 1 | | | | |
| | Arms along the body | $q_{shoulder}^2$ | | | 50 000 | | 50 000 | |
| | Elbows extended | $q_{elbow}^2$ | 50 000 | | | | 50 000 | 50 000 |
| | Hips extended | $q_{hip\ flexion}^2$ | | | | 50 000 | | |
| | Min tilt | $q_{tilt}^2$ | | | 100 | | | end: 1 000 |
| Vision | Spotting | $V_{head}^2$ | 10 | | | | | 10 |
| | Self-motion detection | $\dot{q}_{eye}^2$ | 1 | 1 | 1 | 1 | 1 | 1 |
| | Extreme eye angles | $q_{eye}^2$ | 10 | 10 | 10 | 10 | 10 | 10 |
| | Extreme neck angles | $q_{head}^2$ | 100 | 100 | 100 | 100 | 100 | 100 |
| | Look at the trampoline | $\tanh((\frac{Gx}{Tx}^6+\frac{Gy}{Ty}^6)-1)+1)$ | 100 | | | 100 | 100 | 100 |
| | Fixation on the trampoline | $\arctan((\lVert\vec{G}\times\vec{F}\rVert / \vec{G}\cdot\vec{F}))$ | 1 | | | | | 1 000 |

$$\times \begin{bmatrix}0\\0.25\\0.5\\0.75\\1\\1.25\\1.5\\1.75\\2\end{bmatrix}$$

* Note: All objectives are of type Lagrange, except for the objectives denoted "end: ·", which specify Mayer terms evaluated at the terminal node.

Both acrobatics were generated with and without the inclusion of visual objectives. A global visual weighting was used to multiply the weightings of the visual criteria; eight equally distributed values ranging between 0 (no visual consideration) and 2 (heavy reliance on vision) were tested. The global visual weight was introduced to test various combinations of visual and performance considerations, to find the most realistic compromise. For the condition without visual criteria, the head and eyes were fixed. Since the backward somersault with one twist is executed in straight position, the elbows and hips were fixed as a straight posture is prescribed by the code of points. Animations of the 16 optimal techniques (one per global visual weight per acrobatic) were generated for visual assessment (videos available in supplementary material https://osf.io/eu9tf/).

## 2.3 Comparison of the optimal kinematics

As acrobatics are complex movements at the edge of human motor control capacities, the execution of these motions cannot be assumed optimal. Thus, it is not possible to confirm the optimal techniques generated through predictive simulation by comparing them with experimental data as commonly suggested [19]. Instead, the relevance of the optimal techniques was assessed by expert coaches and judges through qualitative comparison with human movement using animations. Animations of the elite athlete and optimal kinematics were presented in a randomized order to two international judges (FIG certified). Judges were asked to attribute an execution deduction to each kinematics according to the code of points [18]. The optimal and elite athlete kinematics animations were also presented to four international coaches (NCCP level 4). The coaches were provided with side-by-side animations of the techniques with and without a representation of the vision cone representing the gaze orientation. Coaches were asked to consider both animations as the version without the vision cone is more similar to what they are used to see during their coaching practice, and the version with the vision cone would help them better assess the visual strategy at hand. The coaches were asked to rate the techniques using a Likert scale (strongly disagree=1, disagree=2, neutral=3, agree=4, strongly agree=5) regarding the following statements:

| Criteria | 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|---|
| This technique is efficient for aerial twist creation. | | | | | |
| This technique is safe for an athlete to try. | | | | | |
| Overall, this technique seems realistic. | | | | | |
| This technique is aesthetic. | | | | | |
| This technique allows the athlete to get appropriate visual information. | | | | | |
| I would recommend my athletes to use this technique. | | | | | |

Coaches were also asked two open ended questions to provide insights into possible avenue for improving predictive simulations in the future:

*"Do you have any recommendations to improve the simulations?"*

*"Do you have any other comments or suggestions?"*

Due to their brief answers, coaches were asked to verbally elaborate their responses in an informal semi-structured interview. Their answers were analysed to identify strengths and weaknesses in the predictive simulation formulation (thematic analysis) and assess their general acceptability of the techniques (discourse analysis).

## 2.4 Analysis

The optimal kinematics were graphically compared between each other to observe the impact of the global visual weights. The scores attributed by judge's and coaches' to the optimal techniques with and without vision and the athlete's technique were compared. The visuomotor strategies present in the optimal techniques and in the athlete's technique were qualitatively compared.

# 3 Results

### 3.1 Optimal kinematics comparison

In line with our primary objective, optimal techniques for both acrobatics were successfully generated with the inclusion of visual criteria. The optimal kinematics were modified by the global visual weightings (Fig. 2 and Fig. 3). Notably, the first left-arm movement happened quicker as the global visual weight increased to speed up the twist. It is especially noticeable in the middle of the backward somersault with a twist where the twist angle differs by up to 75° between the condition without visual criteria and the condition with the highest visual weight. The global visual weightings also modified the kinematics by increasing the use of the visual strategies (Fig. 7 in Appendix B), sometimes at the price of aestheticism reduction (Fig. 4). The coaches' and judges' detailed appreciation of the optimal techniques expressed during the semi-structures interviews will not be formally presented; they will instead be used to add nuance and refine the discussion section.

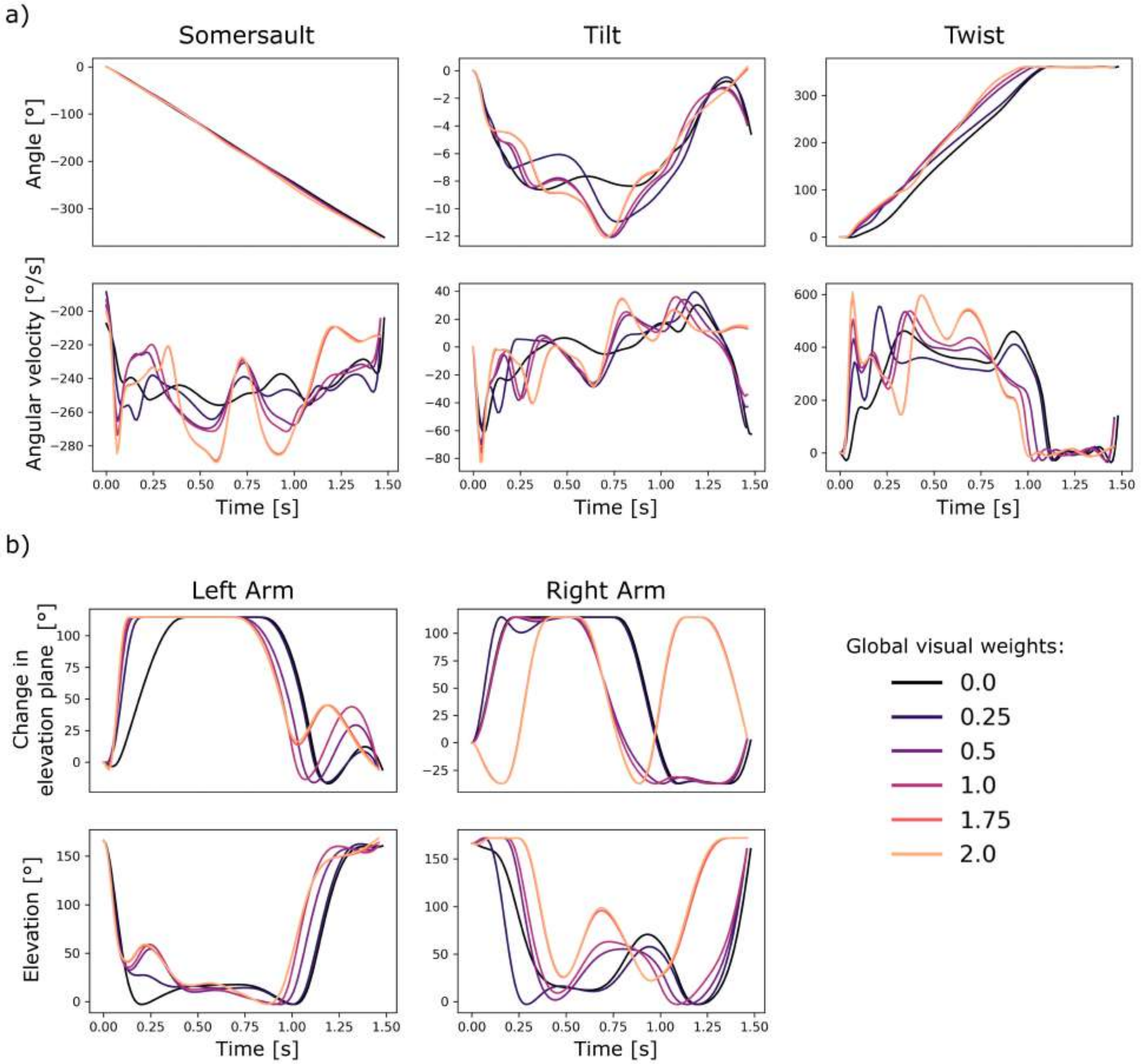

Figure 2. Optimal techniques for the backward somersault with a twist. The global visual weighting factors are presented with color lines; the kinematics presented in black was generated without visual criteria, and the kinematics presented in light peach was generated with the largest global visual weight.

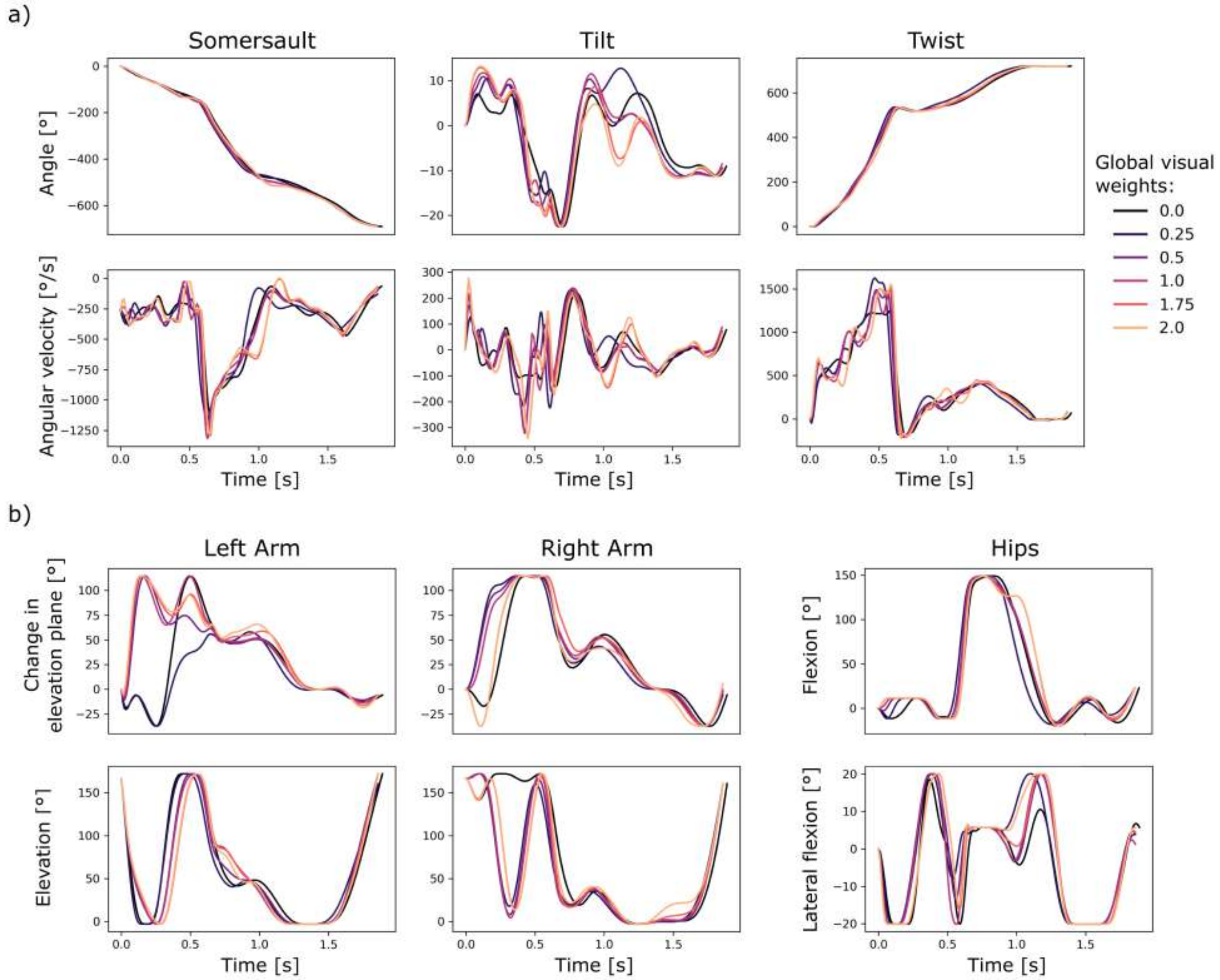

Figure 3. Optimal techniques for the double backward somersault with two twists in pike position. The global visual weighting factors are presented with color lines; the kinematics presented in black was generated without visual criteria, and the kinematics presented in light peach was generated with the largest global visual weight.

## 3.2 Comparison with the athlete's technique

The athlete's technique had a significant contact twist contribution (angular momentum on the twist axis ranging between 18.31 and 73.73 $kg.m^2/s$). Only the aerial twist contributions will hereafter be compared between the athlete's and optimal techniques.

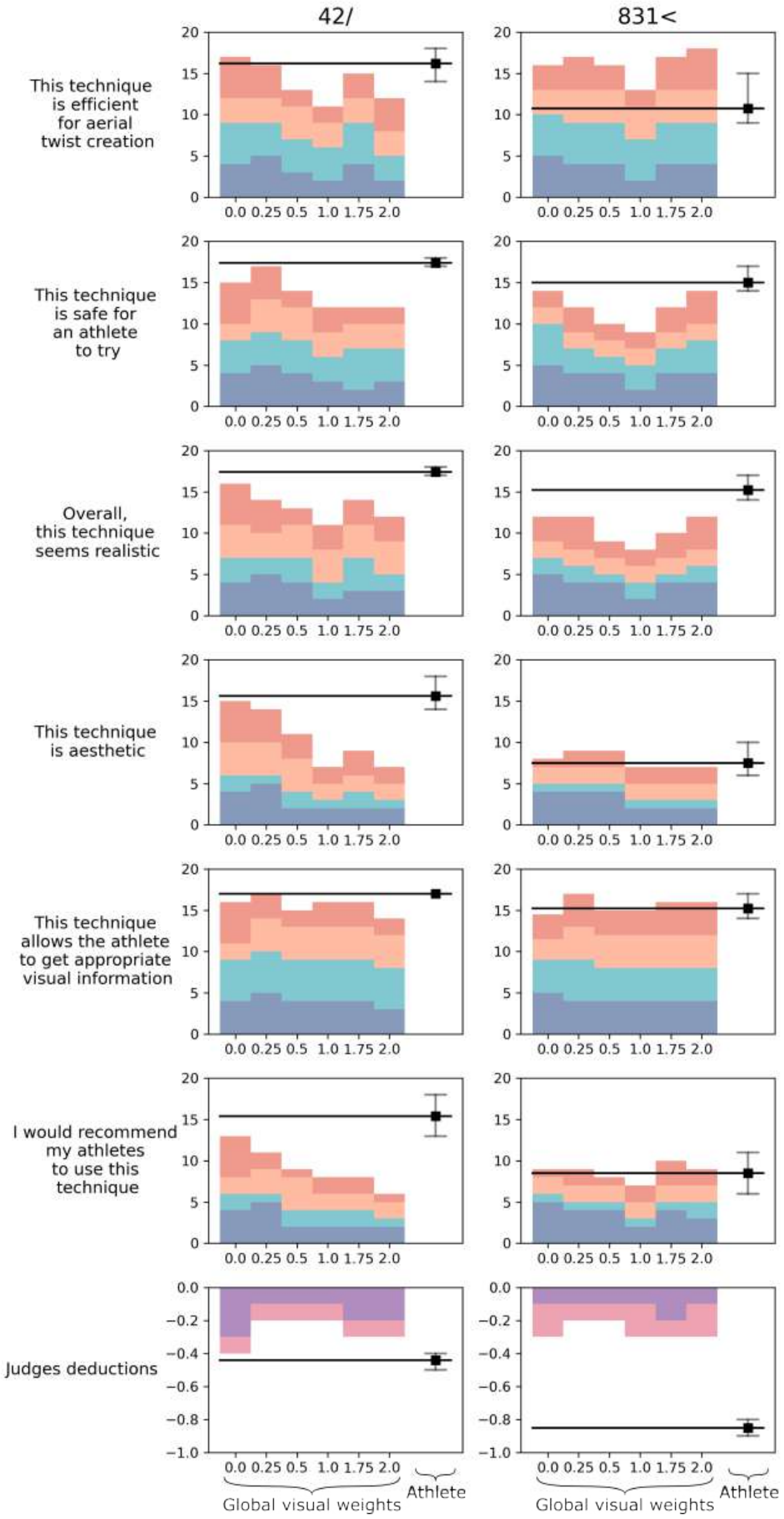

Figure 4. The sum of scores attributed by four coaches (top) and two judges (bottom) to each optimal technique (color bars), the global visual weight is presented on the x-axis. The mean (square) and range (error bar) of the sum of scores attributed to the real athlete's technique. The results for the backward somersault with a twist (left) and the double backward somersault with two twists in pike position (right) are presented. Each color represents the ratings (coaches) or deductions (judges) attributed by the same person. High scores and deductions close to zero indicate a good technique.

### 3.2.1 Backward somersault with a twist

In the optimal and athlete's techniques, the aerial twist was generated using asymmetrical 3D arm lowering. The twist timing and the optimal limb kinematics were modified by the inclusion of visual criteria, with this arm lowering happening noticeably and progressively earlier as the global visual weighting increased. The untilting was performed using a small movement of the right arm before an asymmetrical 3D rising of both arms. Whereas the athlete raised her arms in front of the body, the optimal technique raised the arms on the side of the body. The visual strategies were similar between the optimal and the athlete techniques, where the gaze was oriented towards the center of the trampoline bed after the first $1/4$ twist rotation. It was kept there until the last portion of the acrobatics when the gaze was then oriented toward the forward portion of the trampoline bed. However, the onset timing of these fixations differed; the athlete avoided extreme eye angles by fixating the center of the trampoline bed later and had a more gradual and earlier transition between the fixation of the center of the trampoline and the fixation on the forward part of the trampoline.

### 3.2.2 Double backward somersault with two twists in pike position

Aerial twist creation was similar between the optimal and the athlete's technique, using a 3D lowering of the left arm to the side of the body, followed by a 3D lowering of the right arm in front of the body. The techniques differed from then on. While optimal techniques were accelerating the twist by raising both arms, the athlete waited for the twist to be completed by keeping her arms to the side of her body. The last half twist was performed similarly for the athlete, and the optimal techniques by extending the hips in a circular motion. Similarly to what we observed in the simpler acrobatic, the untilting was performed using an asymmetrical 3D rising of both arms. However, the athlete raised her arms in front of the body, whereas the optimal techniques raised the arms on the side of the body. The visual strategies were also similar between the optimal and the athlete techniques; the trampoline was fixated after the first $1/4$ twist until the beginning of the piking where the trampoline bed got shortly outside of the field of view until the trampoline bed was fixated again after $1\,1/4$ somersault and until landing. As the twist happened sooner in the optimal technique, more extreme eye and head angles were needed to orient the gaze toward the trampoline bed.

# 4 Discussion

Our main objective was to increase the sporting relevance of techniques generated through predictive simulation of twisting somersaults by including visual criteria. This study stands out by asking experts (*i.e.*, coaches and judges) to assess the optimal techniques, allowing to compare the simulated optimal techniques with and without vision with an elite athlete's technique. We found that considering vision in the OCP modified the optimal kinematics; notably, the first arm movement happened quicker to speed up the completion of the first $1/4$ twist as the global visual weight increased. Kinematics were more similar to the athlete's technique, confirming the relevance of adding visual objectives. Coaches appreciated the optimal kinematics for the most complex acrobatic, qualifying the optimal techniques as more efficient for aerial twist creation, comparably aesthetic, and allowing similar appropriate visual information intake than the athlete's technique. However, they expressed concerns regarding the safety and realism of the optimal techniques, preventing their direct adoption. Conversely, judges preferred the optimal techniques to the real athlete's technique.

## 4.1 Inclusion of visual criteria

Including visual criteria into the OCP allowed the reproduction of trampolinists' visuo-motor behaviors previously observed [8, 10, 11] where the athletes dynamically oriented their gaze towards the trampoline bed earlier, compared with the non-vision optimal technique. In a backward twisting somersault, it is possible to see the trampoline bed after $1/8$ twist. Thus, twisting faster is more effortful but allows the trampolinist to see the bed earlier and for a larger proportion of the acrobatics. More subtly, during the double backward somersault with two twists in pike position, we observed the same strategy: the first $1/4$ twist was performed faster when the global visual weights increased. Then, the trend got inverted as the remaining $1 1/4$ twist before picking was performed later to see the trampoline bed longer. This behavior is similar to the athlete's technique; in both cases, the twist in the first somersault was performed slower, leading to delayed picking. The increased similarity between the athlete technique and optimal techniques with larger global visual weights for the double backward somersault with two twists in pike position qualitatively confirms our hypothesis. It highlights the importance of considering the visual needs of athletes when generating acrobatics through predictive simulations. However, the athlete twisted even slower than the optimal technique with the largest global visual weight as she kept her arm on the side of her body during the twist instead of accelerating the twist by bringing the arms up. This delayed twist caused delayed piking, preventing reaching the hip flexion prescribed by the code of points for a perfect pike position, resulting in execution deductions (see "*position of the body*" on Fig. 9 in Appendix D). Moreover, as explained in [20], the supplementary arm movements bringing the arms up in the optimal techniques also increased the somersault stability, facilitating reaching this deeper pike position. This strategy might be interesting for athletes as a perfect pike position is rarely reached by athletes during this acrobatics, as observed in competitions.

## 4.2 Optimal *vs* real kinematics

The differences and similarities between the optimal and the athlete's techniques result from the OCP formulation. The optimal techniques were more efficient for twist creation as the twist could be performed faster and without any contact twist contribution. Thus, coaches acknowledged that athletes could learn from the optimal kinematics to improve their performance. However, they thought the optimal techniques were not realistic enough. Among other things, the optimal techniques showed drastic behavioral changes during phase transitions, which might be undesirable from a motor learning perspective. These behavior changes are due to the instantaneous changes of objective terms weighting at the phase transition. We could use gradual weighting changes instead to match the athlete's smoother behavior. Moreover, some phase transition constraints were chosen to strictly match the code of points. One example is the obligation to show a straight body alignment with all twists completed $1/4$ somersault before landing. This constraint was imposed with a 1° error margin; however, in real-time, judges might not notice larger errors. Leaving larger error margins might give more natural-looking optimal kinematics. In summary, although the optimal techniques could not be directly transferred to athletes, some acrobatic strategies emerging from our predictive simulations, like a quicker lowering of the arm, circular motion of the hips to twist faster, and additional arm movements to gain more stability during the pike somersault could help athletes in their daily practice.

## 4.3 Aesthetics of the optimal kinematics

For the backward somersault with one twist, coaches found optimal techniques less aesthetic than the athlete's technique: arm movements were more noticeable due to a difference in timing of the asymmetrical arm lowering-rising. As the code of points prescribes the arms to be held close to the body, coaches usually hide arm movements behind the body when they are biomechanically necessary. Modifying their athletes' technique makes arm movements less obvious from the judges' point of view (*i.e.*, perpendicular to the trampoline, above trampoline height). Moreover, the aestheticism of the backward somersault with one twist decreased as the weight of the visual criteria increased due to more obvious neck movements used to see the trampoline bed earlier, compromising the body's postural alignment. Including these subtleties in the predictive simulations might improve the aestheticism of the optimal techniques.

For the double backward somersault with two twists in pike position, coaches found the optimal techniques as aesthetic as the athlete's technique. Their main concern was that the optimal technique involved keeping arms overhead to minimize twisting inertia and twist faster. This posture might be in contradiction with the code of points stipulating that "the arms should be held close to the body [...] whenever possible" [18]. As the expression *"whenever possible"* is subjective, coaches apprehended the judges' reaction to the arms overhead twisting technique. Although judges gave larger arm deduction to the optimal techniques, they gave smaller overall deductions, compare with the athlete's technique. This is an encouraging sign of judges' acceptability of the optimal techniques. However, the animations of the optimal techniques represent a perfect case scenario where the technique is executed perfectly, whereas, although the athlete is an expert, she might not have perfectly executed the acrobatic technique her coach wanted her to use. The judges' positive assessment of the optimal techniques means that using the optimal technique might improve the execution score of trampolinists.

## 4.4 Efficiency of the twisting strategies

The code of points does not proscribe contact twist (*i.e.*, creating twisting angular momentum while in contact with the trampoline [21, 22]). However, coaches usually associate it with an excessively arched position and a loss in height in backward acrobatics, both penalized. This arched position lengthens the trajectory to reach the pike position, generally resulting also in an insufficiently piked position, which is also penalized. Coaches found the optimal techniques more efficient for aerial twist creation than the real athlete's technique for the most complex acrobatics. Indeed, the athlete's technique had a large contact twist contribution. Thus, optimal techniques might help athletes trade contact for aerial twist strategies, potentially increasing their execution scoring.

## 4.5 Link between vision and safety

Athletes use visual information to increase landing balance, as shown by comparative studies with vision and non-vision conditions [23, 24]. As landing balance is essential for athlete safety, coaches expressed during the semi-structured interviews that *"visual cues are an essential part of trampolining"* and that they *"teach visual strategies"* to their athletes. However, we did not find any difference in ratings among the optimal techniques with and without visual criteria regarding appropriate visual information intake during the acrobatics. Surprisingly, there was neither a difference with the athlete's technique. Despite the depiction of the visual cone in the animations, the assessment of visual information intake seems challenging. Here are four possible explanations for this phenomenon:

*i.* **Misunderstanding of what is "appropriate visual information" during acrobatics.** Coaches usually instruct their athletes in terms of *visual contact* points, which correspond to gaze fixation targets. This strategy would imply that athletes stabilize their gaze for prolonged periods on specific targets and hop from fixation to fixation. However, we recently observed that elite athletes had a more fluid visual search strategy [8]. They sometimes stabilize their gaze in the environment, but they also fixate their gaze in the head reference frame probably to monitor their own rotation using their peripheral vision (*i.e.*, self-motion detection). Thus, there might be a mismatch between the coaches' instructions and the actual visual strategies used by athletes.

*ii.* **Unfit modeling of the visual behavior of athletes.** To introduce vision in our OCP, we translated the athletes' visual strategies previously observed [8] into mathematical objectives. Despite our efforts, the formulation might still not fully reflect the athletes' visual behavior. Future studies should generate first-person view videos and present them to athletes in a virtual reality headset to get their opinion on the visual strategies.

*iii.* **Inability to see the eye angles.** During training, coaches can observe head but not eye orientation. Here, we introduced a vision cone in the animations, which might have influenced the coaches ratings.

*iv.* **Under-representativeness of the animations.** The optimal and athlete's techniques were presented to coaches using animations. However, coaches are not used to evaluating animations.

## 4.6 Realism of the optimal techniques

The realism score of the optimal techniques was about 1 point lower on the Likert scale than the real athlete's technique. Contrary to our expectations, adding visual criteria did not improve perceived realism. Four potential avenues for improving the realism of the optimal techniques emerged from notes taken by the first author during the semi-structured interviews with coaches: the addition of *i)* spine bending, *ii)* a physiological hip torque constraint, *iii)* a small contact twist contribution, and *iv)* physiological arm range of motion. However, it is worth noticing that coaches gave a realism score of 87% and 76% to the real athlete techniques.

Overall, coaches reported being *"interested"* in the optimal techniques. They were more inclined to recommend the optimal techniques for the most complex acrobatics, probably because its execution in accordance with regulations poses a biomechanical challenge. The complexity of this acrobatics is demonstrated by the broader range of techniques observed on the international stage. This leaves room for technique improvements, and biomechanists' input might be welcomed to help make better technical choices. On the contrary, the backward somersault with one twist is simpler. Thus, athletes have converged toward a unique technique, causing judges to expect this technique. Hence, coaches would not recommend using any other technique, including the optimal techniques generated in this study. Therefore, efforts should be focussed on the predictive simulation of complex acrobatics, as innovation might be more welcomed and more beneficial for the sporting community.

## 4.7 Limitations and perspectives

Apart from the animation representation challenges, this study presents three limitations: *i)* Only four coaches and two judges were interrogated, all Canadians. Further investigations with a larger and more diverse sample might help generalize the results. *ii)* To limit the coaches' and judges' participation to one hour each, the optimal techniques were compared to one athlete's technique. Comparison with more athletes would increase the robustness of the results. *iii)* Like most optimal control studies with an objective composed of multiple terms, the relative weightings of the visual objective terms were fine-tuned manually to find an optimal solution that is visually plausible. Using an inverse approach could help find the weightings that best match athlete techniques.

The optimal acrobatic techniques generated through predictive simulations have gained realism and relevance for the sporting communities [2, 1, 25]. By including visual objectives, this study constitutes one more step toward synthesizing realistic acrobatic techniques. We included visual objectives in the OCP to mimic the athletes' visual behavior. However, to stand out from what athletes already do and generate innovative visuomotor techniques, we should instead model the athletes' internal perception-action coupling mechanisms, as introduced in [26] in a backward tuck somersault.

# 5 Conclusion

This study highlights that the visual needs of athletes should be considered when synthesizing acrobatic techniques as they improve the optimal techniques' relevance for the sporting community. Indeed, some acrobatic strategies emerging from the optimal techniques generated in this study could help athletes improve their execution scores. As experts' assessments of our optimal techniques highlighted the strengths and weaknesses of our problem formulation, we recommend using expert opinion to cocreate predictive simulations.

# Author contributions

**Eve Charbonneau:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing original draft, Visualization, Funding acquisition, data collection, interviews. **Thomas Romeas:** Review & Editing, Supervision, Funding acquisition. **Annie Ross:** Review & Editing, Supervision, Funding acquisition. **Mickaël Begon:** Conceptualization, Writing, Review & Editing, Supervision, Funding acquisition.

# Disclosure of interest

The authors report no conflict of interest.

# Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used *ChatGPT* and *Grammarly* in order to enhance writing correctness and clarity (spelling, grammar, sentence reformulation). After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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# Data availability statement

The videos and questionnaires presented to the coaches and judges are available here https://osf.io/eu9tf/. The code used for the generation of the predictive simulations and all analysis is available here https://github.com/EveCharbie/VisionOCP [27].

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