

Analyzing Gaze Behavior in Complex (Aerial) Skills

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(Received February 2, 2012, accepted May 9, 2012)

Abstract. Complex skills with aerial phases, such as somersaults or release-regrasp skills make up about 45 % of all elements in artistic gymnastics. The underlying mechanics of these skills have been studied extensively, and visual information is thought to assist gymnasts in skill performance. However, empirical evidence on the role of gaze behavior and its interplay with movement behavior in complex skill performance in gymnastics is still limited and obvious gaps in the literature exist. Therefore, the aim of this study was the development of an eye-tracking prototype that allows for the measurement of gaze behavior during complex (aerial) skill performance. After presenting the structure and the analysis procedure of the system, two selected examples for the application of the system will be discussed.

Keywords: eye-tracking, fixations, movement analysis.

1. Introduction

Skills with aerial phases, such as somersaults or release-regrasp skills, make up about 59 % of all elements in women's artistic gymnastics and about 32 % in men's artistic gymnastics [1]. The underlying mechanics of such skills have been studied extensively (for a review see [2]). Performing such skills places specific demands on athletes' spatial orientation, and vision has been proposed to be integral in providing athletes with the necessary cues for spatial orientation [3, 4]. However, empirical data on visual information pickup in complex aerial skills is still limited and obvious gaps in the literature exist. This may at least in part be explained by methodological problems in existing studies, namely omitting to measure gaze behavior during complex aerial skills [3]. Therefore, this study was concerned with designing and assessing an eye-tracking system prototype to measure gaze behavior during complex (aerial) skill performance.

Visual information has been shown to assist gymnasts in landing somersaults [3, 4, 5-7], and it is thought that this might result from a prospective type of control of body orientation during the flight phase [8, 9]. In these studies, however, athletes gaze behavior was not measured but visual information pickup was manipulated when performing complex skills, often showing no or only minor influences on skill performance. From this it is questionable, if manipulating visual information pickup may lead to adaptive gaze behavior [10], or if the manipulated visual information is even needed in complex skill performance [9, 11]. None of the aforementioned studies integrated the measurement of gaze behavior in their designs, and one cannot be certain that a manipulation of visual information did or did not influence gaze behavior. From this it may be concluded, that the development of an eye-tracking system to be used in aerial skills may serve two functions: First, on a methodological level, it may help to measure athlete's gaze behavior in different tasks and under different conditions. Second, on a theoretical level, the measurement of gaze behavior in complex aerial skills may help to answer questions related to the adaptability of gaze behavior or the functions of specific gaze behavior parameters such as fixations or saccades in complex aerial skill performance.

There are initial attempts to record gaze of athletes, coaches, and judges, which provided significant insights in what underlies athlete's performance and perceptual ability [12-17]. However, in the systems used, the observer was mainly in a stationary situation, observing pictures or video sequences, rather than moving around in a natural environment. The spatial and temporal resolutions of the devices were questionable, and in some systems, the participant's field of view was significantly constrained by cameras placed in the field of view or by looking through specific apertures. Finally, early "portable" eye-tracking systems often forced

the participant to carry backpacks with recording and/or transmission devices in them, or were connected by cable to stationary recording devices (for an overview see [18, 19]).

While early eye-tracking systems were useful to measure eye movements in stationary participants observing pictures or video-sequences, nowadays, researchers are more interested in the coupling between gaze behavior and motor performance in complex skills [20]. Several methods, such as electro-oculography, scleral contact lens techniques, and video-oculography techniques were utilized in a wide variety of studies to measure gaze behavior parameters [18, 21]. However, when it comes to more complex situations or skills, video-based approaches have proven to be the most promising since these systems are almost non-reactive whilst providing satisfying temporal and spatial resolution [20]. Most commercial systems use miniature cameras that videotape the movements of the eyeball and specific image processing algorithms extract meaningful information such as the centroid of the pupil, which is for instance an indicator of gaze direction.

The so-called *vision-in-action system* can be seen as a prototypical video-based eye-tracking system used in sports [22]. It records the center of the pupil and a corneal reflection point, which originates from an infrared light source that is directed to the participant's eyeball. By measuring the differences between the two entities, the system determines where the gaze is located in space with regard to a frontal scene camera that pictures a part of the athlete's visual field. However, since participant's gaze is measured with regard to a frontal scene camera, gaze can hardly be measured during fast head movements, because fast movements of the head may lead to a blurring of the frontal camera. Furthermore, frontal cameras used in eye-tracking systems usually do not record the participant's complete field of view but rather a small section therein. Therefore these systems are applicable for tasks such as basketball free throw or golf putting [22, 23], but are barely useful for measuring gaze behavior in complex aerial skills, such as somersaults with and without twists.

Taken together, measuring gaze behavior during complex (aerial) skills is still a challenge for scientists and practitioners on a methodological level, leading to significant developments on a theoretical level. Therefore it was concluded, that the development of an eye-tracking prototype that can be used to measure gaze behavior during complex (aerial) skills is a necessary step, and was therefore defined as the aim of this study.

2. Methods

Given the current state of the art concerning mobile eye-tracking systems [18, 20], and the goal to measure gaze behavior in complex aerial skills, this study was concerned with designing and assessing an eye-tracking system to serve this goal. Since the eye-tracking system should be usable in different contexts, initial interviews were conducted with five international high performance coaches and another three researchers of the German Sport University Cologne, the University of Tübingen, and the National Training Center for Trampoline Gymnastics Bad Kreuznach (Germany) to identify which functions the eye-tracking system should serve best. The functions identified were:

1. usable with complex (aerial) skills such as somersaults with and without twists
2. light-weight and ease of use for coaches and athletes
3. usable inside and outside as well as in the lab and in the field
4. wireless connection to recording device
5. combinable with different movement analysis systems
6. real-time gaze behavior analysis and feedback

From the results of the interviews, a first prototype was developed. This prototype is usable with complex (aerial) skills, is light-weight, is usable inside and outside, has a wireless connection, and is combinable with different movement analysis systems. The basic structure, its calibration procedure, and further information on usability are presented in the next sections of this manuscript.

2.1. Basic Structure of the System

The prototype system consists of a modified bicycle helmet with an attached wireless miniature camera, four reflective markers and a power supply ensuring light-weight and ease of use (approximate weight 250 g). Figure 1 shows a schematic diagram of the system. An infrared miniature camera is fixed on the front edge of the bicycle helmet and its optical axis projects to an infrared mirror (dielectric heat reflecting hot mirror), which is inclined against the optical axis of the participant's eye. This mirror transmits visible light and reflects infrared light, allowing the infrared camera to record images of the participants' eyeball, while not

perturbing the participant's field of view. The infrared mirror is fixated on the miniature camera and the helmet in order to prevent shakes that may occur during high accelerations of the head. Both, the infrared camera and the infrared mirror can be aligned with the right or left eye of the participant.

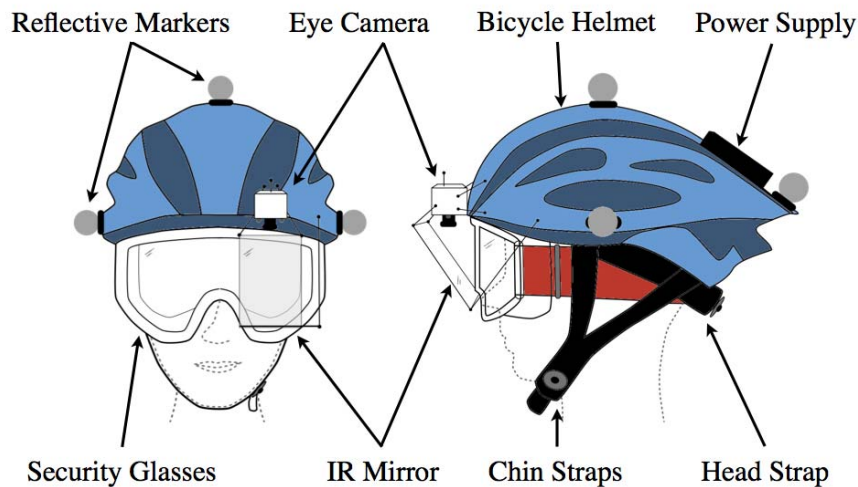


Fig. 1: Schematic diagram of the eye-tracking system illustrated in this manuscript. The reflective markers are attached to the bicycle helmet when using the system together with a movement analysis system. The front camera is attached to the bicycle helmet when the system is used without a movement analysis system.

The miniature camera operates at 50 Hz and transmits the pictures of the eye at 2.4 GHz to a stationary receiver. The receiver is connected to a personal computer, which records the pictures of the camera. The participant is allowed to move about 50 meters around the receiver when there are no obstacles between the participant and the receiver. A power supply (9 Volts) is attached at the back of the helmet energizing the miniature camera. The bicycle helmet is held in place with chinstraps and another strap around the back of the head. While wearing the bicycle helmet, the participant also wears security glasses consisting of a polycarbonate pane and another soft strap. Four additional reflective markers are fixed on top, on the back and on both sides of the helmet for measuring the orientation of the helmet, when using the eye-tracking system together with a movement analysis system.

2.2. Analysis Procedure

The most common application of the system in motor control research is to combine it with a movement analysis system. Figure 2 illustrates the steps when combining the system with a movement analysis system. The infrared miniature camera records the movements of the eye while the movements of the body are *synchronously* recorded by a movement analysis system.

Depending on the movement analysis system, the X-, Y- and Z-coordinates of significant body landmarks and the reflective markers on the helmet are measured directly (e.g. infrared system) or after the movement sequences of the body were captured (e.g. direct optical system). From these coordinates, motions of the body landmarks in three-dimensional space as well as the orientation of the eye-tracker helmet are calculated [24]. From the motions of the body landmarks and from additional measurements (e.g. force measurements), kinematic and/or dynamic variables of interest are calculated (e.g., phase durations, motion of the center of mass, linear and angular motion parameters of body segments and the whole body, or reaction forces). All components of the system are modular, therefore allowing exchanging them with regard to specific empirical questions. For instance, the eye camera can easily be exchanged with a camera operating at higher recording frequencies.

A standard *calibration procedure* is conducted prior to measuring gaze during the experimental task. The participant is placed in front of, and two meters away from a calibration wall, facing a 25-point LED grid at a height of 1.50 meters. The 25-point grid is setup in a way that the four corner points correspond to rotations of the eyeball of +33 to -33 degrees in the vertical and the horizontal direction. The participant is asked to place his or her chin to an adjustable platform while facing the midpoint of the 25-point grid. The front edge of the eye-tracker helmet is pressed against a U-shaped metal rod. The 25 calibration LEDs are highlighted in a random fashion. The participant has to focus each highlighted LED. The X- and Y-coordinates of the

centroid of the pupil, the corneal reflection point/s and at least one additional reference point are measured while the participant fixates his or her gaze to each of the 25 LEDs. This is usually being done in a semiautomatic manner by movement analysis software (e.g., WinAnalyze 3D, [25]), using a pupil tracking algorithm such as the dark pupil [18] or the starburst algorithm [26]. The corneal reflection points are usually visible between +20 and -20 degrees in the horizontal and vertical direction. They are tracked when they are visible and used to correct the estimation of the centroid of the pupil, leading to a slightly higher precision of the system for measurements when the corneal reflection points are visible (measurement error $\pm 0.5^\circ$) than when they are not visible (measurement error $\pm 1.0^\circ$). In the next step, the resulting X- and Y-coordinates of the centroid of the pupil are offset against the X- and Y-coordinates of the reference point. This leads to 25 coordinate pairs, which correspond directly with the calibration grid. However, when the eyeball rotates more than ± 15 degrees, the projection of the pupil to the 2D calibration plane is no longer linear, and the rotation in horizontal direction depend in part on the rotation in vertical direction and vice versa [27]. Therefore, a set of 14 quadratic regression equations is calculated, relating the coordinates of the centroid of the pupil to gaze direction in three-dimensional space.

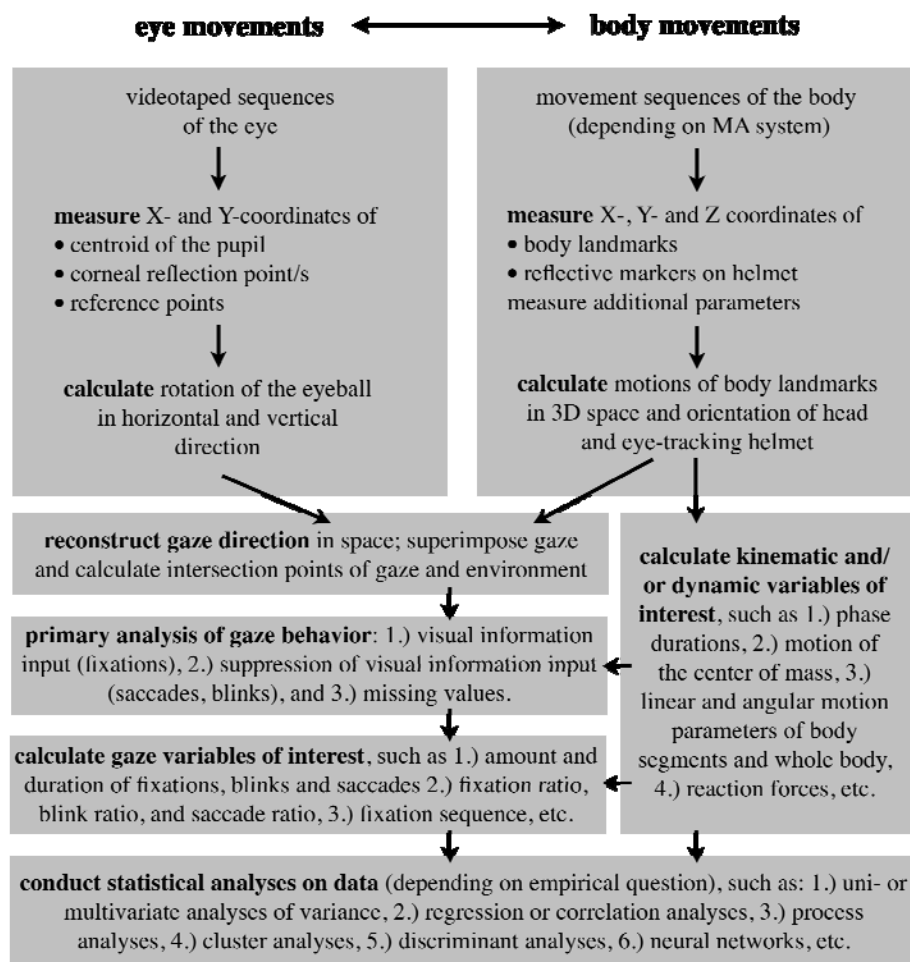


Fig. 2: Flow-chart of analyzing gaze behavior in complex skills while using the eye-tracking system in this study together with a movement analysis system.

When *reconstructing gaze direction in space* in aerial skill performance, first the X- and Y-coordinates of the centroid of the pupil, the corneal reflection point/s and an additional reference point are measured after the movements of the eye were recorded (see Figure 3, pictures 4 to 5). This is again being done in a semiautomatic manner by movement analysis software, using a pupil tracking algorithm such as the dark pupil [18] or the starburst algorithm [26]. The reference point (e.g. cheekbone or nasal bone, see Figure 3, picture 4 and 5) is used to control for unwanted shakes of the system, which may occur during high accelerations of the head. As in the calibration procedure, the corneal reflection points are tracked when they are visible, and used to correct the estimation of the centroid of the pupil. The resulting X- and Y-coordinates are offset against the X- and Y- coordinates of the reference point. Depending on the resulting X- and Y-

values, the regression coefficients of the quadratic regression equations are adjusted, and the rotation of the eyeball in horizontal and vertical direction is calculated. The angular data of the eyeball is integrated in the orientation data of the eye-tracking helmet from the movement analysis data to reconstruct the gaze direction vector in space. The gaze direction vector is mathematically expressed as a linear slope in parametric form, following the equation:

$$g : \vec{r} = \vec{r}_o + \lambda \cdot \vec{u}.$$

In this equation, \vec{r}_o is the position vector of the participant's tracked eye in three-dimensional space, \vec{u} represents the direction vector of the gaze direction, and λ is a scalar, which is used to calculate the intersection points of the gaze vector and the environment. If the environment was measured and integrated in the data pool, the intersection points between the gaze direction vector and the environmental surfaces can easily be calculated from the aforementioned parametric form.

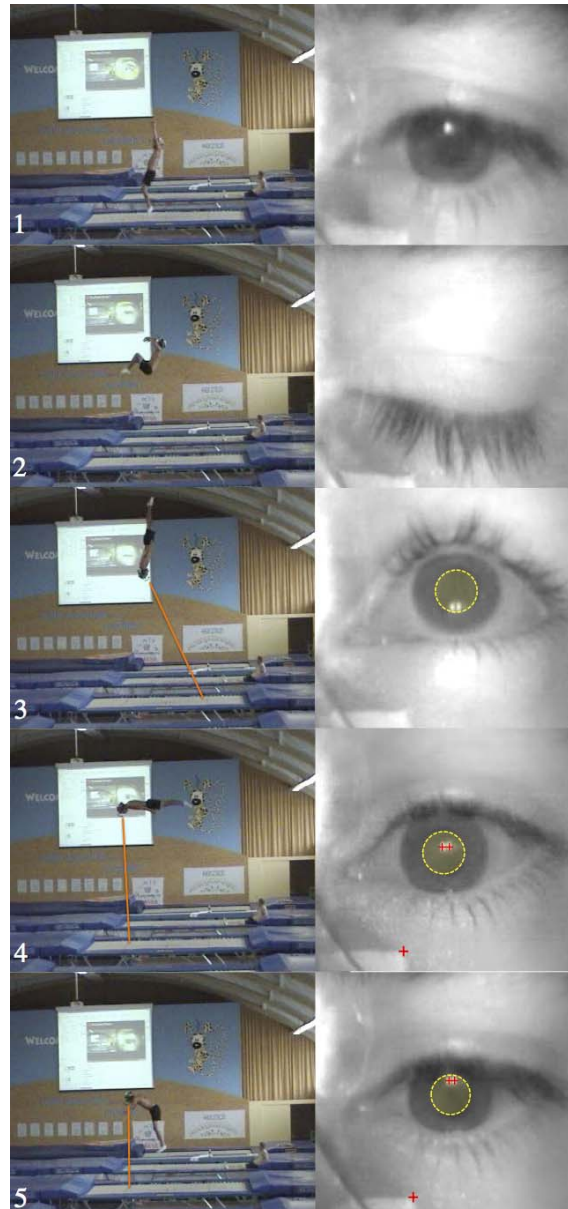


Fig. 3: Split screen sequence illustrating the eye-tracking system when used with an optical movement analysis system. *Left*: video pictures from the movement analysis system. *Right*: video pictures of the eye-tracking system. In pictures 3 to 5, the pupil is highlighted and gaze direction is superimposed on the digital video picture. Picture 2 illustrates a blink. Pictures 4 to 5 show a fixation to the same location in the environment.

As soon as the gaze direction in three-dimensional space is reconstructed for a specific aerial skill, a *primary analysis of gaze behavior* variables of interest is conducted. First, the onset and offset of an aerial skill, as well as its motor phases are defined [20]. Both, the onset and offset should comprise significant

events in the temporal structure of the aerial skill. For instance, when analyzing a somersault on the trampoline, it could be useful to set the onset five frames prior to the initial contact of the feet with the trampoline bed in the take-off phase. The offset could in turn be set 15 frames after the gymnast's initial contact of the feet with the landing mat in the landing phase (see for example [28]). It should be ensured, that the total duration includes all the critical gaze and motor information required to answer the study question/s. Given, that aerial skills differ in their significant events, it is advisable to set the onset and offset with regard to existing biomechanical studies and with the aims and empirical questions of the study. Skill onset and offset should remain constant when analyzing different participants performing the same aerial skill. In the next step, phases of information pickup (fixations) and phases of suppression of visual information input (saccades, blinks), are analyzed with the help of gaze behavior protocols. Therefore, a trained researcher codes the gaze in terms of the type of gaze used (fixations, saccades, blinks, and missing values/other, [18, 20]). In the system's standard protocol, gaze is coded as "fixation" (incorporating smooth pursuit movements) if it is directed for a minimum of 100 ms to the same object or location in the environment. Gaze is coded as "blink", when the eyelid closes the eyeball for a minimum of 60 ms. Gaze is coded as "missing values/other" if the centroid of the pupil could not be estimated due to blurred video recordings or strong shakes of the system. The remaining frames are coded as "saccades". The gaze behavior protocols are offset against a significant event in the temporal structure of the aerial skill. Therefore usually the skill onset is used. This procedure allows the practitioner to analyze gaze behavior within and across the motor phases of the aerial skill [20].

Gaze variables of interest are calculated from the gaze behavior protocols. Because the kinematic and gaze data were synchronized when collected, it is possible to determine the temporal structure of gaze with regard to the movement kinematic data. First, *gaze variables can be calculated with regard to the total movement time*. In the system's standard protocol, 1.) amount of fixations, 2.) average fixation duration, 3.) amount of blinks, 4.) average blink duration 5.) amount of saccades and 6.) average duration of saccades can be analyzed. Amount of fixations, blinks, and saccades are simply count from the gaze behavior protocols. The durations are usually averaged using spreadsheet computer software. Since different trials within and between participants usually differ in total movement time, it may also be wise to normalize gaze variables to the total movement duration. From the amount and duration of fixations, blinks and saccades, the fixation ratio ($ratio_f$), blink ratio ($ratio_b$) and saccade ratio ($ratio_s$) can be calculated by the following formula:

$$ratio_{(f,b,s)} = \frac{\sum_{i=1}^n t_{(f,b,s),i}}{MT} \cdot 100\%$$

To calculate for instance the fixation ratio, the durations of all measured fixations ($t_{f,i}$) are summed up and divided by the total movement time (MT). The same calculation is applied for blink ratio and saccade ratio. For instance, if a participant shows three fixations with durations of 200, 250 and 210 ms, and the movement time is 1200 ms, then the fixation ratio is calculated as: $660 \text{ ms} / 1200 \text{ ms} \cdot 100 \% = 55 \%$. This value indicates, that the participant fixated his or her gaze about 55 % of the total skill to objects or locations in the environment. Fixation ratio, blink ratio, and saccade ratio should theoretically add up to 100 %. If they do not add up to 100 %, then the remaining value indicates the relative amount of gaze that was coded as "other". Normally amount and duration of fixations, amount and duration of blinks, and the calculated fixation and blink ratios are of primary interest in motor control research, since little difference has been found in saccadic times across participants [19].

In addition to analyzing gaze behavior with regard to the total movement time, it may also be necessary to analyze *gaze behavior with regard to the distinct motor phases* of an aerial skill. Amount and average duration of fixations, blinks, and saccades may be analyzed with regard to the defined motor phases of the aerial skill. However, since fixations, blinks and saccades may span two connected motor phases, it may be more useful to calculate the fixation, blink and/or saccade ratio with regard to the different motor phases, indicating the relative amount of information pickup (fixation ratio) or relative amount of suppression of information pickup (blink ratio, saccade ratio). Finally, depending on the aims of the study and the empirical questions, *gaze behavior can be analyzed with regard to objects and locations* in the environment in which the participant performs the aerial skill. Locations define the spatial and environmental constraints within which the participant performs the aerial skill. Objects normally move within the environment. Nevertheless, each object and each location provide unique information important to understand how the visual system contributes to motor learning and control [20]. Therefore it may be useful to analyze the

aforementioned gaze variables of interest with regard to (significant) objects and/or locations in the environment. If the researcher is for instance interested if gymnasts direct their gaze more to the springboard or to the vaulting table during the approach run when performing a vault, he or she should analyze gaze behavior with regard to the springboard and the vaulting table (locations/objects) throughout the approach run (motor phase). If the question is more related to the overall information pickup in different phases of the approach run (e.g. first half vs. second half), then variables such as fixation ratio should be analyzed with regard of the different motor phases. Depending on the analyzed aerial skill, it may also be necessary to conduct a sequence or process analysis, especially if the researcher is interested in the transition probabilities of fixations from one location or object to another (for more details see [18]).

Performing *inferential statistical analyses* is the last step in the analysis procedure. The analysis procedures used depend on the empirical questions and the design of the study at hand. For instance, if the researcher is interested in differences in gaze behavior and movement kinematics or dynamics between several experimental trials (e.g. first trial vs. 10th trial), tasks (e.g., different skills with similar structure), conditions (e.g., full vision vs. vision restricted to the first half of the skill), and/or groups (e.g., experts vs. apprentices), then univariate or multivariate analyses of variance with or without repeated measurements are applicable. If the researcher is more interested in relationships between several biomechanical parameters and gaze behavior parameters, he or she will use correlation analyses, linear or nonlinear regression analyses. Other more exploratory statistical procedures, such as process analyses, cluster analyses, discriminant analyses or neural network modelling may be useful to target specific empirical questions [29-32]. The use of different statistical methods (e.g., evaluating differences vs. evaluating relationships; inferential vs. exploratory) may give significant insights in how gaze behavior is connected with motor performance in complex aerial skills. It is, however, not intended to discuss these approaches but encourage the intrigued reader to lookup the sources just mentioned.

3. Selected Results

Two selected examples from the application of the eye-tracking system together with a movement analysis system in motor control research will be illustrated in this paragraph. It was decided to choose examples from artistic gymnastics, since complex (aerial) skills make up the majority of skills in this sport.

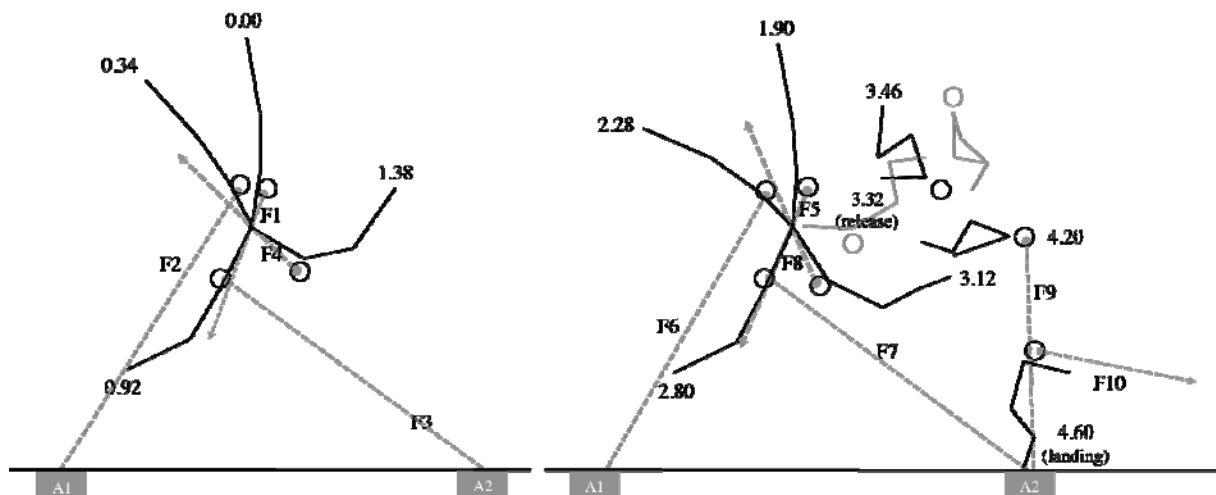


Fig. 4: Stick-figure sequence of the double salto (right) with a preparatory giant swing (traditional technique) on the high bar (left) of one expert gymnast. The numbers indicate the time structure of the skill. The dotted lines represent fixations and fixation directions during the skill. The thickness of the dotted lines indicates fixation duration. F1 to F10 indicate the sequence of fixations. A1 and A2 indicate fixation's areas of interest. It was found that fixations directed towards A2 corresponded directly with the landing distance of the gymnast.

The first example comprises the application of the eye-tracking system in gymnasts performing giant swings with dismounts on the high bar (see Figure 4). The question was to explore relationships between gaze behavior and movement behavior. The experimental task was to perform a double tucked salto as dismount after preparatory giant swings with the traditional technique [33]. Gymnasts' kinematic parameters were measured with an optical movement-analysis system while gaze behavior was measured by using the portable and wireless eye-tracking system described in this manuscript. The *double salto* performed by one expert gymnast presented in Figure 4 was characterized by a sequence of 10 fixations. The first, fourth, fifth

and ninth fixation were directed towards the high bar. The second and sixth fixations were directed towards the rear mat. The third, seventh and ninth fixation were directed towards the front mat and corresponded with the landing position at the end of the dismount, indicating the potential functional of these fixations for both, a prospective type of control during the giant swing as well as during the last part of the dismount in order to prepare the touch down. It was concluded, that directing the gaze towards the landing mat serves the function to organize movement execution in a way that best serves the performance of an intended dismount.

The second example comprises the application of the eye-tracking system in gymnasts performing single turns on one leg with either eyes open (without occlusion) or eyes closed (with occlusion, see Figure 5). The aim of this application was to analyze the relationship between visual information pickup and the coordination between head and eye movements in complex movements. Figure 5 presents the rotation of the eyeball together with the rotation of the head in a gymnast performing a single turn on one leg. When examining movement kinematics, a difference of head rotation during the end phase of the skill performed under the two conditions becomes apparent. The gymnast over rotates the single turn when visual information pickup was suppressed (with occlusion) when compared to when visual information pickup was not suppressed. During the turning phase there is furthermore a clear fixation visible when visual information pickup was not suppressed. The ratio of this fixation was 50% when related to the turning phase and 21% when related to the duration of the whole skill. One may speculate that a training gymnast may use ocular-motor information during turning when visual information pickup is not suppressed. This information could potentially be used to correctly estimate the actual rotation state with regard to neither over rotating nor under rotating the turn.

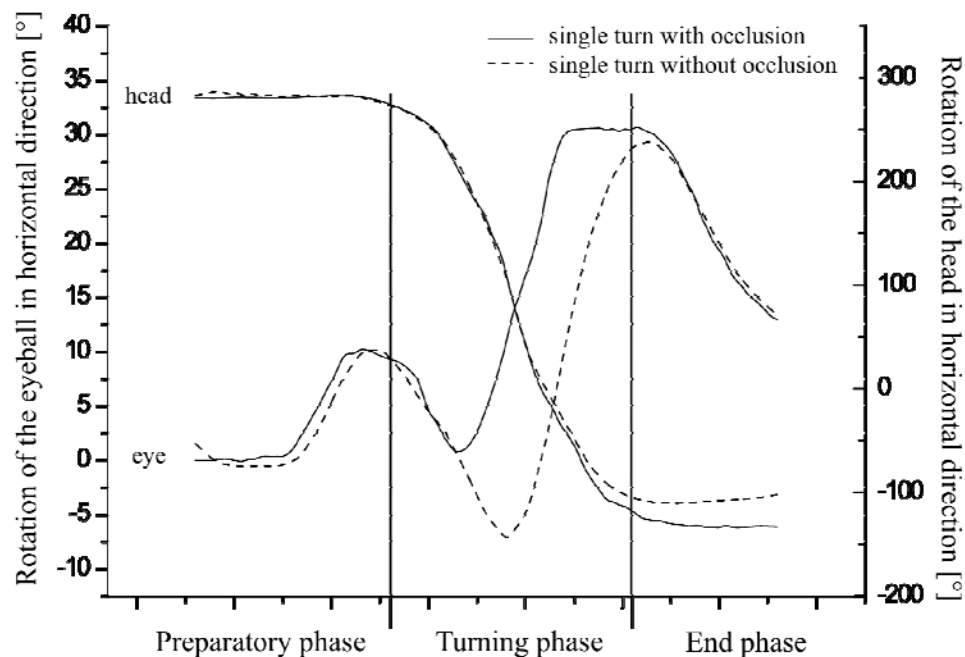


Fig. 5: Rotation of the eye-ball and the head in horizontal direction in a gymnast performing a single turn on one leg either with eyes open (without occlusion) or with eyes closed (with occlusion).

4. Discussion & Conclusion

The main aim of this manuscript was to describe an eye-tracking prototype that can be used to measure gaze behavior during complex (aerial) skills. This was identified as a necessary step since measuring gaze behavior during complex (aerial) skills may lead to significant developments on a theoretical level because there is only sparse empirical evidence on the role of visual information pickup and gaze behavior in complex (aerial) skills. For this purpose, and in accordance to the opinions of experts from research and application, the design of the eye-tracking system should serve different functions. The actual prototype is usable with complex (aerial) skills, is light-weight, is usable inside and outside as well as in the lab and in the field, exhibits a wireless connection to the recording device, and is combinable with different movement analysis systems. Depending on the empirical or experimental question, the operator may use the system with or without additional systems, such as 2D or 3D movement analysis systems. The operator may either calculate some basic gaze variables of interest or perform some in-detail analysis, such as regression

analyses or process analyses. The prototype in its current form comprises neither a function for real-time gaze behavior analysis, nor for real-time feedback. One could furthermore think about using eye tracking in environments such as under water. The two mentioned aspects would be interesting challenges for future research and development.

5. Acknowledgements

The authors thank Damian Jeraj for helpful comments on the first draft of our manuscript.

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