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Projet EYE TRACKING

Suivi automatique du point de regard chez l'humain

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I. Contexte et présentation générale de l'opération :

Eye vision is one of the most important means for humans to interact with their surroundings [1]. In sports, athletes always use their eyes strategically to pick up relevant and reliable information for action [2], [3]. The long duration of the point of gaze toward an area of interest corresponds to a visual fixation [4]. The positions and the duration of visual fixation are two factors of gaze behaviors that explain skilled performance in sports [5]. Traditionally, expert athletes exhibit fewer but longer visual fixations than non-experts, which reflects their skills to pick up relevant and reliable information for action [6]. Thus, a substantial duration of the visual fixations on the relevant object helps athletes in compromising between the time-consuming and the amount of needed information [5]. Moreover, visual fixations are rarely independent but often organized each other in a meaningful sequence and related to action, to pick up affordances. Therefore, gaze behavior has to be trained at the same time as motor behavior to enhance their performances [7]–[9]. Consequently, for each type of sport, large datasets that have relations between gaze behaviors (e.g. locations and durations of points of gaze) and performance outcomes (e.g. time, speeds, and accuracy) need to be acquired to study how gaze behavior affects the sport outcome.

In sport climbing, the analysis of gaze behaviors also informs climbing outcomes, notably because previewing routes could influence climbing performances [10], [11]. In climbing, climbers often explore the opportunities of action offered by the climbing wall for selecting suitable and accurate movements and for avoiding unnecessary or jerky moves [12], [13]. It is important to note that route prospecting is usually conducted before and during climbing [14]. Based on a direction-based concept, during climbs, climbers alternate between different motion phases: immobility (for instance to visually scan the wall), hold exploration, pelvis movement (e.g. for postural regulation purposes), and global moving [15]. In particular, climbers spent 10% during climbing for the immobility phase, 65% for hold exploration, 1% for pelvis movement, and 24% for global moving [15]. Climbers especially used their eyes for exploring the holds [14] with the distinction between visual fixations that are executed in combination with hand movements (i.e., performatory fixations) and fixations that are executed when participants were not moving to a new handhold (i.e., exploratory fixations) [16]. Moreover, visual fixations could be used to explore holds (and adjusted hand grasping) and to find the route among the climbing holds to guide hand and foot movements [12]. For instance, when skilled climbers performed on a route composed of different types of handholds (irregular routes), in comparison to a route set with only two types of handholds (regular routes), they made fewer fixations (222 vs. 281 fixations per trial), suggesting that climbers were more careful and thorough in their gaze behaviors with the regular route because of the additional technical demands it presented. Conversely, the irregular route afforded a more superficial visual exploration with the use of more frequent saccades between holds [17]. These findings suggested how skilled climbers exploited irregularity in the environment. More recently, another study investigated the exploratory activity (both visual and motor) during skill acquisition and transfer in a climbing task. The results showed that the number of exploratory hand movements and fixations decreased with practice. Although the number of exploratory movements also decreased on the transfer routes following practice, the number of fixations was higher than on the learning route, suggesting that, with learning, participants relied more on exploration from a distance to adapt to the new properties of the transfer routes [18].

Despite this body of literature highlighting the importance of gaze behaviors on climbing outcomes, further research would be necessary to understand how gaze behaviors would satisfy the dual demand of visual control: the accurate control of the current movement; and the anticipatory search for environmental demands that will constrain the future movements [19], [20]. To reach that goal, research on gaze behavior should go beyond the analysis of visual fixations and could investigate the time-series of points of gaze and motor behavior (e.g. motion of the limbs or the center of mass).

Knobelsdorff et al., 2020 [21], studied the constraints between the complexity of visual planning routes and the climbing performance of the on-sight climbing sport. This study analyzed the relation between the fingertip strength and the complexity of gaze transition patterns during route preview. However, during the climb, only the movement trajectory of the hip was studied with fingertip strength. Moreover, this study also tried to map local points of gaze on a wall image, but the mapping process was conducted manually and not during climbs. Additionally, Neiuwenhuys et al., 2008 [16] analyzed gaze behavior during climbs, but only the local information of fixations (e.g. total fixation duration, number of fixations, and average fixation duration) were analyzed. The on-climbing routes drawn by points of gaze have not been analyzed. To analyze the on-climbing prospective routes, mapping points of gaze from local views to a global wall is the first requirement [21], [22]. However, this issue has not been solved, especially in an automatic manner.

Regarding eye-tracking technologies for sport climbing, various types of devices (e.g. fixed, mobile, and head-mounted) have been increasingly deployed [23], but mobile eye-tracking devices were mostly (with ~85%) used in sportive applications [24]. In sport climbing, both wired (i.e. [16]) and wireless eye-tracking devices (i.e. [10], [21]) were used. During climbs, these devices need to be wireless to improve the dynamic ranges of players [16]. Recently, wireless and mobile eye-tracking glasses (i.e., Tobii Pro Glasses 2 [2]) could be used to track points of gaze in real-time with high accuracy. However, only using these eye-tracking devices, positions of points of gaze on the global scene could not be obtained straightforwardly. Although most studies have tried to combine these eye-tracking devices with other types of sensors such as optical cameras [16], inertial measurement units (IMUs) [15], force sensors [21], motion capturers [21], etc., for tracking the global head positions of the performer or for locating the local scenes in the global scene, the global points of gaze on the global scene have not been computed.

II. Objectifs recherchés :

Because of all the above reasons, this research tried to generate a suitable dataset ready for analyzing the effects of gaze behaviors on climbing performances. In particular, a large dataset including 2,460 climbing cases was acquired from the Rouen University, France.

During the climbs, the climber wore a Tobii Pro Glasses 2 for acquiring local views and points of gaze in real-time (Fig. 1d). For analyzing the effects of gaze behaviors on climbing performances during the climbs, the points of gaze (POGs) and the climbing holds (CHs) from the local views needed to be mapped onto a global space, such as a climbing wall. The following three main tasks should be conducted for processing that large climbing dataset.

First, a software tool was developed for post-processing the recorded videos for each climbing case. The recorded video did not have exactly the starting and ending moments for analyzing the climbing performance. Moreover, the raw POG data acquired by the Tobii Pro Glasses were not synchronized with the video frames, so they needed to be post-processed and synchronized with the video frame rates. The objectives of this stage were for processing the climbing cases to have starting moments, ending moments, and local POGs. As shown in Fig. 1, the climbing case video was started when the instructor touched a climbing hold (Fig. 1a), the climbing progress was counted from the climber touched both hands on the first climbing hold (Fig. 1b), and the climbing progress was ended when the climber touched his/her hand on the final climbing hold (Fig. 1c).

(c) Ending Moments of the Climbing Trial

(b) Starting Moments of the Climbing Trial

(a) Signal from an Instructor for Starting the Climbing Action

(d) A climber is performing a climbing trial

Figure 1. *The period of a climbing case: (a) the climbing video started when the instructor touched a climbing hold; (b) the climbing action started when the climber touched both hands on the first climbing hold; (c) the climbing action ended when the climber touched his/her hand on the final climbing hold; and (d) during climbing, the climber wore a Tobii Pro Glasses 2 for acquiring local views and POGs in real-time.*

Second, due to the huge number of local frames throughout all climbing cases, an automatic computational method for mapping the POGs and CHs from the local views to the global climbing walls should be developed. To verify various methods for investigating the optimal computational method, we proposed two main processing concepts: image-processing-based and machine-learning-based. The objectives of this main task were the optimally fast and robust processing method for computing the global POGs and CHs.

Third, the optimal method was applied to process all frames of the 2,640 climbing cases. The objectives of this main task were the processed dataset including the global positions of POGs and

CHs. These global positions were synchronized with the local views of the climber during the climbs to form a time-serial data of POGs on the global climbing wall coordinate system. In particular, Figure 2 shows an example of computed POGs and CHs in a climbing wall. In each climbing case, all frames were automatically processed to detect/classify the POGs and CHs in the local views. Moreover, artificial landmarks designed as four-disk groups were also detected supporting mapping of the local positions of POGs and CHs to the global climbing wall.

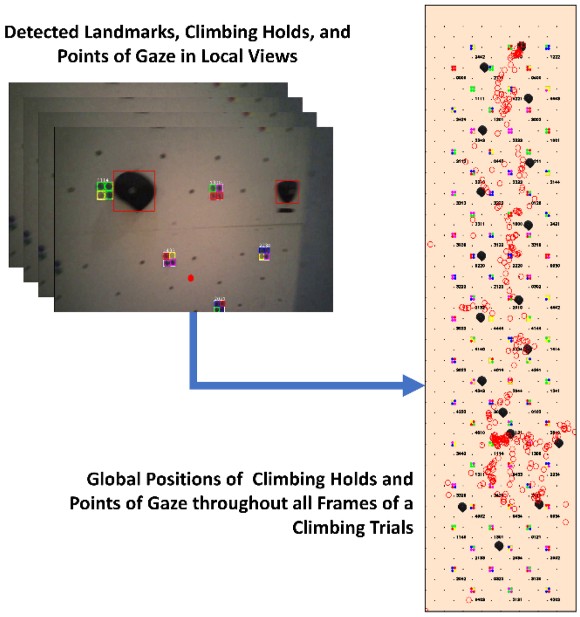

Figure 2. *An example of POG and CH global mapping of a climbing case. All frames of the climbing case were processed individually for detecting local positions of POGs and CHs during the climb. The global positions of the POGs and CHs on the climbing wall were computed thanks to the detected landmarks on each local frame. All global positions of POGs and CHs were synchronized with video frames of the climbing case as time serial data. This time-serial dataset will be used for analyzing the effects of gaze behaviors on climbing performances.*

III. Actions réalisées sur la période :

III.1. **Researching plan:** eye-tracking in sport climbing

The detail of the research plan is shown in Fig. 3. The post-doc research was during more than 10 months from 15/02/2021 to 31/12/2021. The plan was divided into three main periods.

The first period was from 15/02/2021 to 15/04/2021. During this time, the software tool for processing all climbing videos was developed. The dataset of raw climbing videos and raw POG data acquired by the Tobii Pro Glasses 2 was collected from the Rouen University, France. The Tobii Pro Glasses and its software development kit were then investigated. The task was continued by developing a graphical user interface (GUI) for cutting the climbing video and synchronizing POG data with the climbing video frames. Finally, with the developed GUI, all 2,640 climbing cases were cut and processed for later processing steps.

The second period was from 16/04/2021 to 15/06/2021. During this time, the first concept of global mapping the POG into a global climbing wall was developed. I first reviewed the literature for updating processing methods for global mapping and localization in robotics using computer vision approaches. The image-process-based POG global mapping method was then developed, and an article was also written.

In the third period, from 16/06/2021 to 15/09/2021, I developed a new POG and CH method for more robustly and accurately localizing the POGs and CHs in the climbing walls. After the 5-fold cross-validation procedure, an optimal POG and CH localization method were developed. Finally, I wrote an article about this developed method.

In the fourth period, from 16/09/2021 to 31/12/2021, all climbing cases were processed using the optimal POG and CH localization method. All processed dataset was delivered to the Rouen University, France for further development. After the delivery, I wrote a report about my post-doctoral research period and moved to the Centrale Lille Institue for continuing my start-up project. During my time at Centrale Lille Institute, I continued to revise the first and second articles and submitted them to suitable journals. I will also be available for cooperating with the Caen Normandy University and the Rouen University with their future research projects.

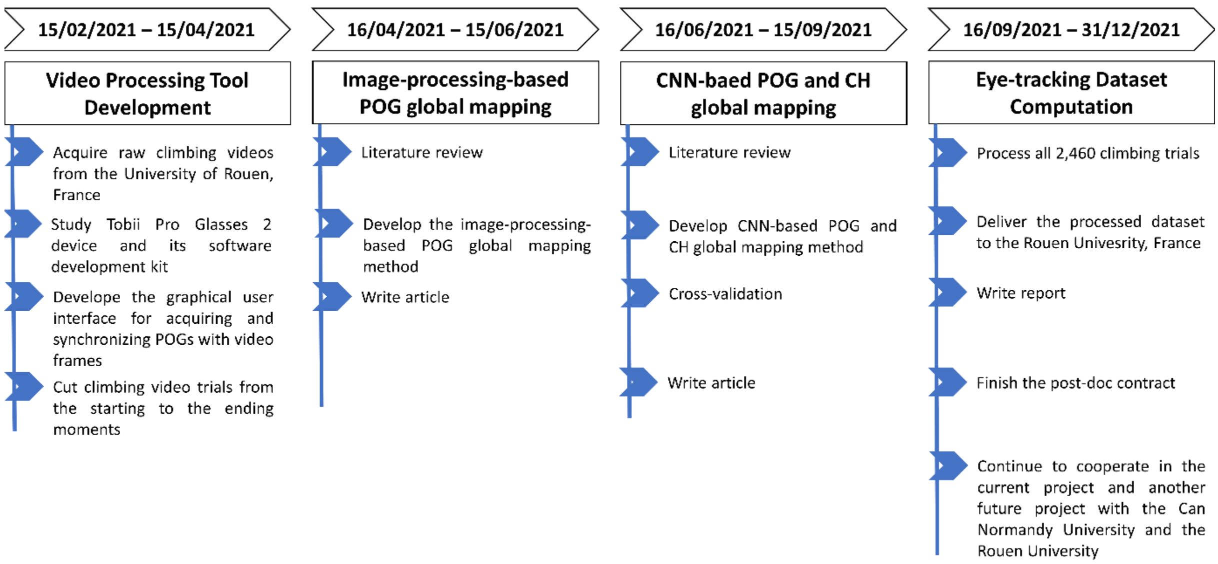

Figure 3. *Researching plan of the "Eye-tracking in sport climbing" post-doc from 15-02-2021 to 31-12-2022.*

III.2. **First task:** design a software tool for processing recorded videos

Fig. 4 showed an illustration of the GUI of the software tool. The user used the software to input the raw project file generated from the Tobii Pro Glasses software tool kit. The software then detected the list of recorded videos from the raw project and other related information about the climbers and recorded metadata. The metadata included trial identification numbers (IDs), climbers' names, and recorded dates. The user would then use the sliding bars for selecting the starting and ending moments of the climbing actions. The starting and ending moments of a climbing period are illustrated in Fig. 1. After pressing the cutting button in the GUI, the cut videos and the synchronized POGs were then saved in a selected folder. The GUI also supported the visualization of the local view and the global climbing wall.

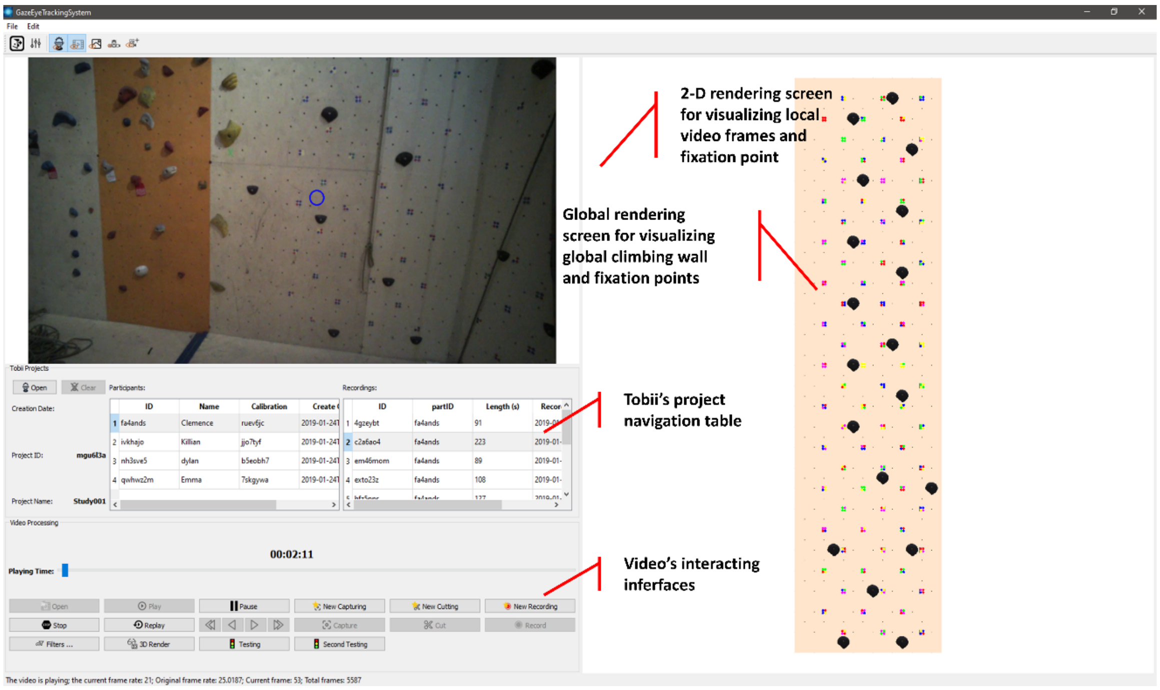

Figure 4. *The software tool for cutting the climbing cases and synchronizing the POGs with climbing video frames.*

III.3. **Second task:** development of an optimal POG and CH global mapping method

III.3.1. Image-processing-based POG global mapping

The image-processing-based POG mapping method is illustrated in Fig. 5. In particular, the mapping procedure included three main stages: (1) gaze data acquisition, (2) landmark detection, (3) landmark-based fixation mapping, (4) optical flow-based fixation mapping, and (5) point of gaze frame filling.

(1) Regarding the gaze data acquisition (Fig. 5a), a Tobii Pro Glasses 2 [25] was used to acquire local image frames and local points of gaze on the image coordinate system. This device was mounted on a climber's head during his/her climbing. The fixation data were synchronized with the image frames with a frame rate of 25 frames per second (FPSs).

(2) Regarding the landmark detection (Fig. 5b), in each Red-Green-Blue (RGB) image frame, landmark positions in the local image coordinate system were detected. To detect landmarks on a local frame, the following sub-procedures: ellipse detection, 4-disk-group selection, color detection, and landmark code estimation were conducted.

(3) Regarding the landmark-based fixation mapping (Fig. 5c), landmarks were designed as four-color-disk groups, each of which has four color disks arranged in a squared shape for robustly being detected and classified. All landmarks were equally distributed on the climbing wall. The local positions of the detected landmarks on the local frame and the global positions of these detected landmarks on the climbing wall were used to estimate a homography transform. The global position of the point of gaze on the climbing wall was computed by transforming the local position of the point of gaze on the local frame using the estimated homography transform.

(4) Regarding the optical flow-based fixation mapping (Fig. 5d), during the climbs, local landmarks could not be detected on some frames due to low light conditions or motion blurs. The optical flow method was applied to infer the current global point of gaze using the previous point of gaze and the homogeneous relations among consecutive frames.

(5) Regarding the fixation frame-filling (Fig. 5e), when both landmark-based and optical flow-based strategies could not detect local landmarks due to obstacles or too large motion blurs, a linearizing strategy was applied for filling the global points of gaze on the missing frames.

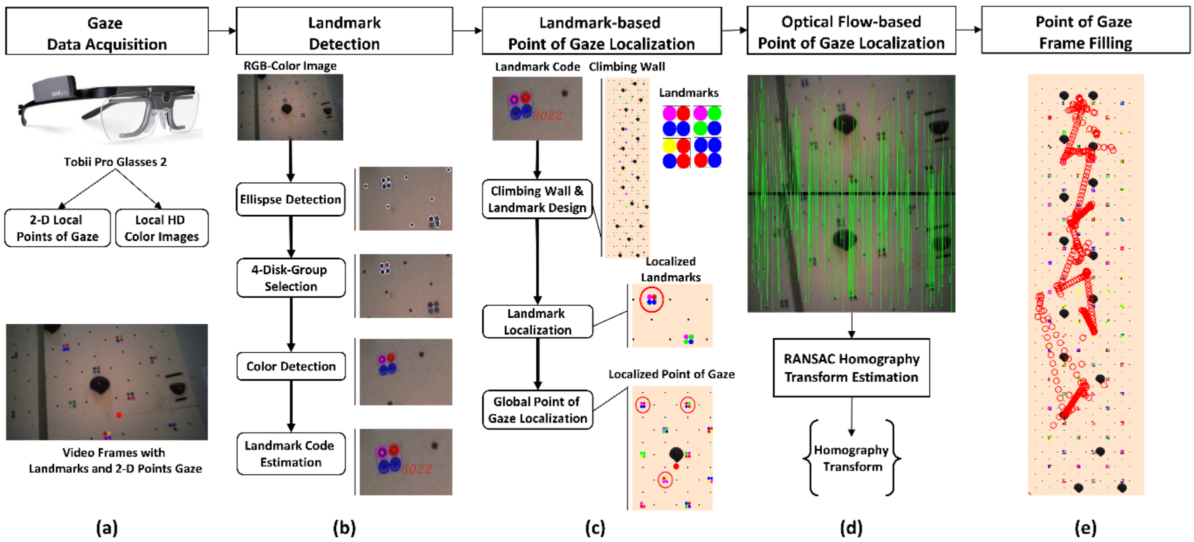

Figure 5. *The image-processing-based POG global mapping procedure: (a) dataset acquisition, (b) landmark detection, (c) landmark-based point of gaze localization, (d) optical flow-based point of gaze localization, and (e) point of gaze frame filling.*

III.3.2. Convolutional Neural Network-based POG and CH global mapping

The overall processing procedure of the CNN-based POG and CH global mapping method is illustrated in Fig. 6. In particular, the procedure includes (1) dataset acquisition, (2) 5-fold cross-validation, (3) landmark & climbing hold detection/classification, (4) CH localizing & clustering, and (5) POG localization.

In dataset acquisition, 10 climbing cases were selected randomly from the 2,460 processed videos for manually POG and CH localization. For each frame of a climbing case, we selected and labeled the local CHs, four-disk landmarks, and color disks inside the local views. These datasets were used for model selection and training.

In model selection and training, five-fold cross-validation was applied to select the optimal training strategy and structure of the CNN network. In the separate training strategy, three object detectors and classifiers were trained separately for detecting/classifying four-disk groups, color disks, and climbing holds. In the combined training strategy, only one object detector & classifier was used for detecting four-disk groups, color disks, and climbing holds. Five different versions of YOLO (You Only Look Once) [26] were used for training the object detection & classification models.

In the landmark & climbing hold detection and/or classification, the optimal validated object detection & classification model was used for detecting and classifying the four-disk groups, color disks, and climbing holds. The landmarks were formed and classified thanks to the detected color disks and four-disk groups.

In the climbing hold localization, the local positions of the detected CHs were mapped to the climbing wall based on the homography transform from the color disk positions in each local view to the color disk positions in the global climbing wall. The mapped CHs throughout all frames of a climbing case were clustered to form the computed CHs. Moreover, in the POG localization, the local positions of POGs in local views were also mapped onto the climbing wall based on the correspondences between the local and the global positions of the color disks.

The outputs of the whole procedure were the global positions of the CHs and POGs on the climbing wall. Moreover, the global positions of POGs were synchronized with the video frames for later gaze behavior analysis.

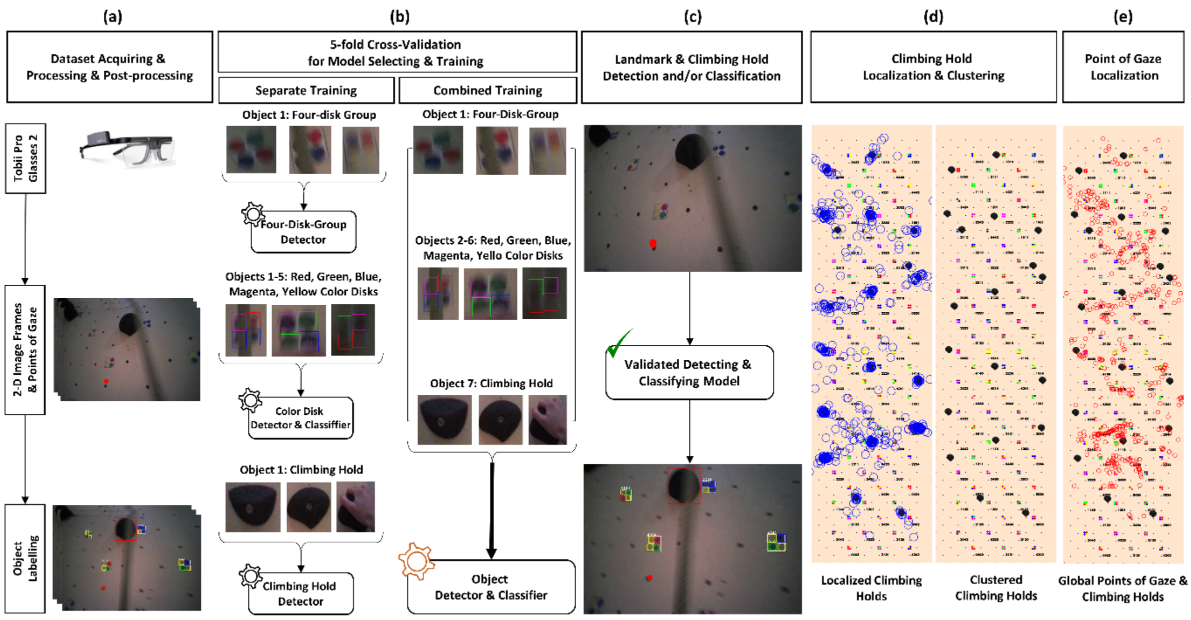

Figure 6. *The overall procedure of the POG and CH global mapping is based on the CNN concept: (a) the dataset was generated from each frame of the 10-randomly selected climbing videos using a manual localization process; (b) the acquired dataset was then used for selecting the optimal training strategy and structure of the CNN-based object detection & classification models; (c) the optimal model was used for detecting and classifying landmarks and CHs in the local views; (d) the global positions of the CHs were computed based on the detected landmarks; (e) the POGs were also mapped onto the climbing wall based on the detected landmarks.*

III.4. **Third task:** computation of global POGs and CHs for all climbing cases

The optimal automatic POG & CH mapping method was employed for computing global CH and POG for all processed climbing case videos. As shown in Figs. 7a, 7b, and 7c, the 2,640 climbing cases were organized into three groups of climbing walls (Fig. 7a). In each wall group, the appropriate climbing cases were separated based on their identification number (Fig. 7b). In each climbing case, the data included a cut video, local points of gaze, and other motion data from the Tobii Pro Glasses 2 (Fig. 7c). The detailed descriptions of the input dataset are explained in the following.

- **cutVideo.mp4**: The file contains the climbing period from the starting moment, when the instructor touches a finger on the wall, to the ending moment, when the climber touches his/her hand to the final climbing hold. The frame rate of the video is 25 frames per second.
- **cutVideo_*.json**: The file contains all acquired data from the Tobii Pro glasses 2 in JSON format. The acquired data, for example, are 2-D & 3-D points of gaze, glass acceleration, glass rotation speed, left/right gaze direction, and left/right pupil center. All of their values are time serial data and synchronized with the video frames.
- **cutVideo_*.mp4**: This file is the same as cutVideo.mp4. I saved it for the system execution.
- **fixation2DPoints.csv**: The file contains the 2-D relative coordinates of the points of gaze in the image coordinate system in time serial data. The coordinates are synchronized with the video frames.
- **fixation3DPoitns.csv**: The file contains the 3-D coordinates (in millimeters) of the points of gaze in the glass coordinate system in time serial data. The coordinates are synchronized with the video frames.
- **glassOmegas.csv**: The file contains rotation speeds (yaw, pitch, and roll in degree) of the glasses in the glass coordinate system in time serial data. The rotation angle speeds are synchronized with the video frames.
- **glassAcclerations.csv**: The file contains the 3-D acceleration (m/s^2) of the glasses in the glass coordinate system in time serial data. The acceleration values are synchronized with the video frames.
- **left/rightGazeDirections.csv**: The file contains left/right 3-D gaze direction vectors in time serial data in the glass coordinate system. The direction vectors are synchronized with the video frames.
- **left/rightPupilCenters.csv**: The file contains left/right 3-D positions (in meters) of the left/right eyes in the glass coordinate system. The position values are synchronized with the video frames.

- **recordingInfo.csv**: The file contains bio-information of the climber in the current trial. The information includes recording ID, participant ID, participant name, and recording date of the current trial.

As shown in Fig. 7d, the computed outputs included the climbing wall image with global CHs, POGs, and landmarks. Moreover, landmark global coordinates, global POG coordinates, and local POGs which are all synchronized with the video frames were also saved in each climbing case. The computed output videos were also created for later analyses.

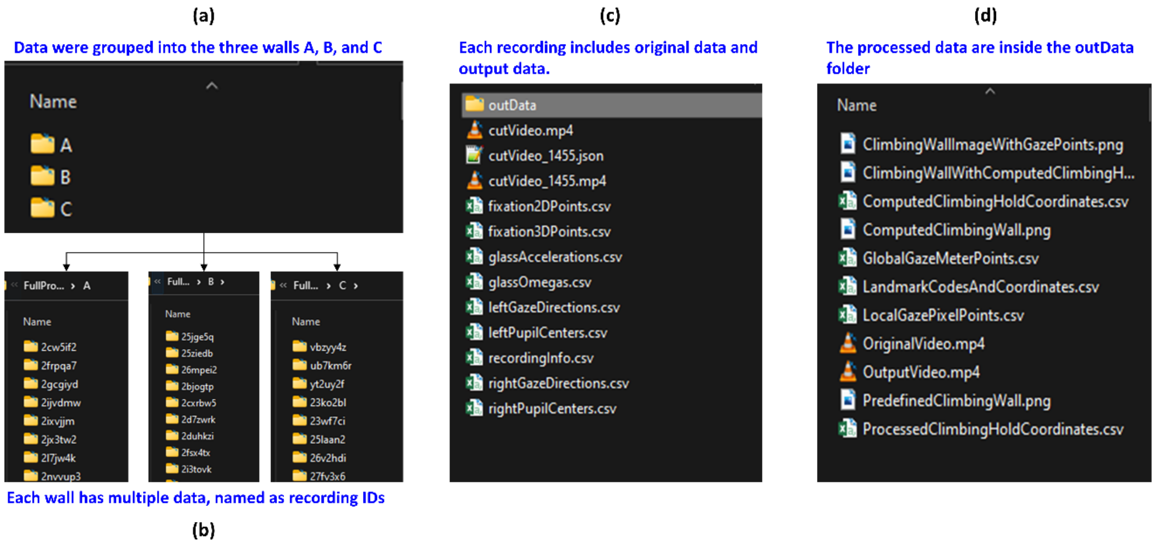

Figure 7. *The organization of the processed climbing cases from a raw dataset acquired from the Rouen University, France: (a) the dataset was organized into the three wall configurations; (b) each climbing case was identified by its ID number; (c) all types of the input data were saved inside each trial folder; (d) the computed output data were saved in the outputData folder.*

IV. Résultats obtenus:

Three main results were obtained during the post-doc research period. The first result was the software tool for processing raw datasets acquired by the Tobii Pro Glasses 2 and its tool kit. The second result was methods for global mapping of the local CHs and POGs to the global climbing wall. The third result was the full processed dataset of 2,640 climbing cases including all types of necessary data for the analyses of gaze behaviors on climbing performances.

The software package and its instruction documents can be downloaded via the link https://www.dropbox.com/scl/fo/fr37obusr72a9lsbba38g/h?dl=0&rlkey=6y2fddbjmk75gdbzhn5sunew0.

Regarding the image processing-based method for mapping the POGs and CHs onto climbing walls, using classical image processing techniques, the success rates of landmarks detection and POGs computation were relatively low (~10.87%). When combined with the optical flows and other regression techniques the success rates could be enhanced up to 30.08% and 85.72%. However, the accuracy of the POG detection was

reduced when enhancing the success rates. When using the classical image processing techniques, the mean distance error between the computed POGs and the ground-truth POGs was 0.130 m. When using the optical flow technique, the mean error increased to 0.174 m. When the regressing technique was applied, the error was up to 0.278 m. The POG mapping results were illustrated in Fig. 8 and Fig. 9. The detail of the image-processing-based POG global mapping method was presented in the manuscript via the link:
https://www.dropbox.com/scl/fo/v9zpww4fx50rf7ty5zbjw/h?dl=0&rlkey=4kve5ipl221sdksjss45jsz22.

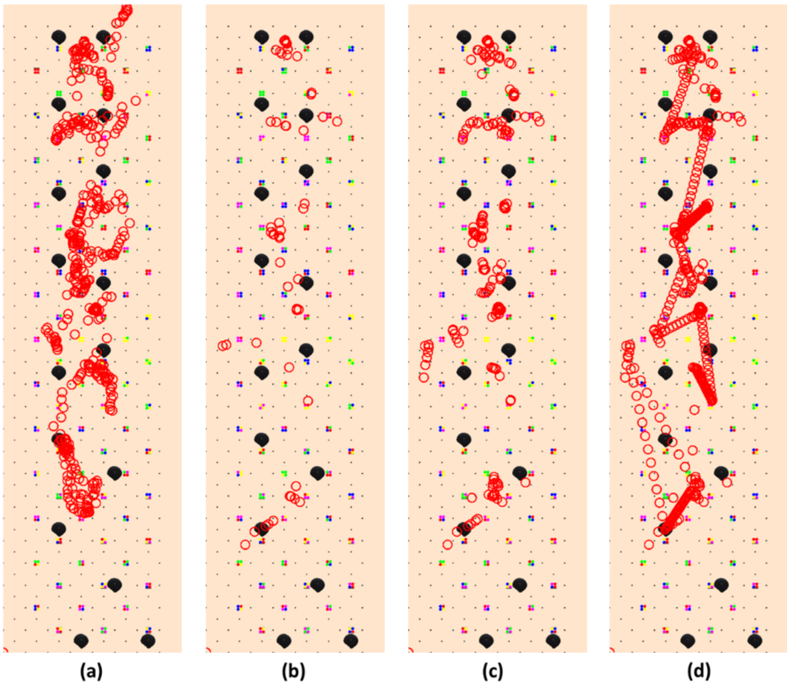

Figure 8. *The global points of gaze on a wall configuration C were computed using different mapping strategies: (a) using semi-automatic global mapping, (b) using only landmark-based mapping, (c) using both landmark-based and optical flow-based mapping, and (d) filling points of gaze on missing frames.*

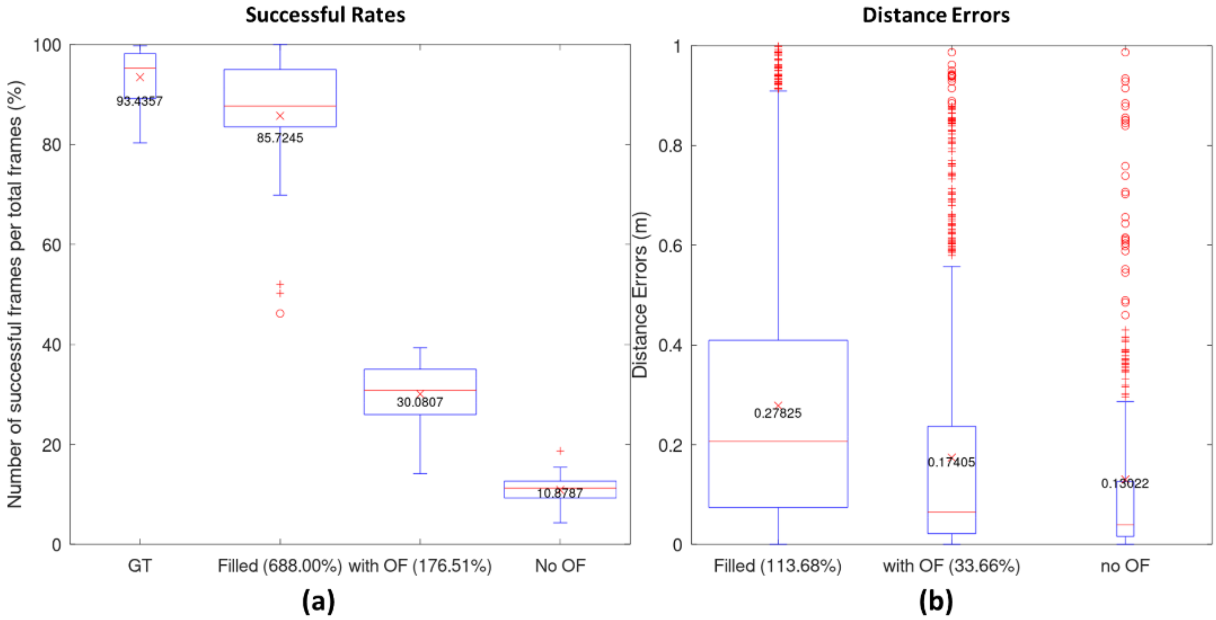

Figure 9. *(a) Success rate of the detected frames using manual (GT), image-based with optical flows (OF), and image-based without optical flows (OF) methods; (b) Distance errors between the points of gaze computed using the image-based with/without OF methods and ones computed using the semi-automatic method. Note that the red crosses inside the boxplots represent the mean values of the success rates and distance errors.*

Regarding the CNN-based POG and CH global mapping method, after the five-fold cross-validation process, we discovered that the separate training strategy was the optimal one, and the YOLO V5 was also the optimal CNN structure of the four-disk group, color disk, and climbing hold classifiers. Those conclusions are shown in Fig. 10. In particular, Fig. 10a shows that the average precisions of the object detectors using separate training are always higher than ones using the combined training using the YOLO V4 structure [27]. Moreover, in Fig. 10b, the success rates of POG and CH using the separate training are higher than ones using the combined training. Moreover, the distance errors of the computed POGs and CHs using the separate training are lower than the ones using the combined training (Fig. 10c). Additionally, when applying the separate training strategy in different versions of YOLO (V1, V2, V3, V4, and V5), the distance errors of the computed CHs and POGs using YOLO V4 are the best throughout the five versions of YOLO, as shown in Figs. 11a, b. The detail of the CNN-based was presented in the ongoing manuscript via the link: https://www.dropbox.com/scl/fo/2za9birjgo46asiqyjug8/h?dl=0&rlkey=7q95c21fsdtcx6p6442iu0dym.

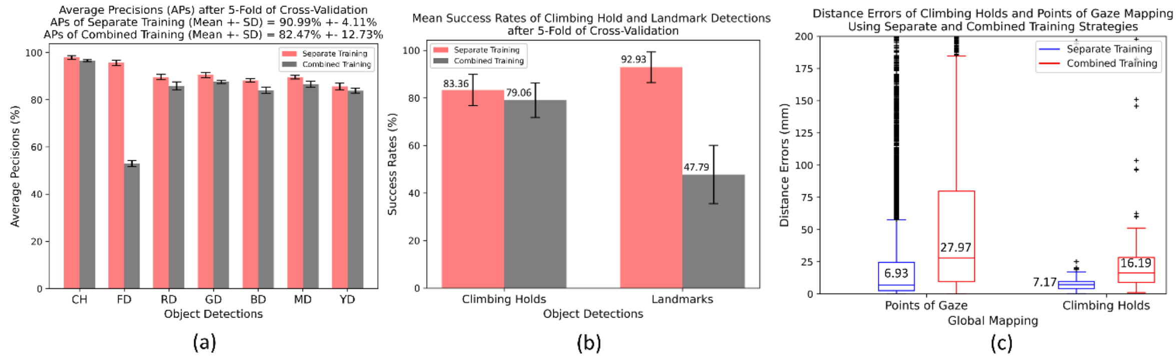

Figure 10. *Accuracies of object detections and global localization after the 5-fold cross-validation using the separate and combined training strategies: (a) average precision values, (b) success rates of climbing hold and landmark detections (mean values are reported beside the bar charts), and (c) distances errors of climbing holds and points of gaze global localization using the CNN-based POG and CH global mapping. Mean values are reported in the bar charts, and median values are reported in the box plots.*

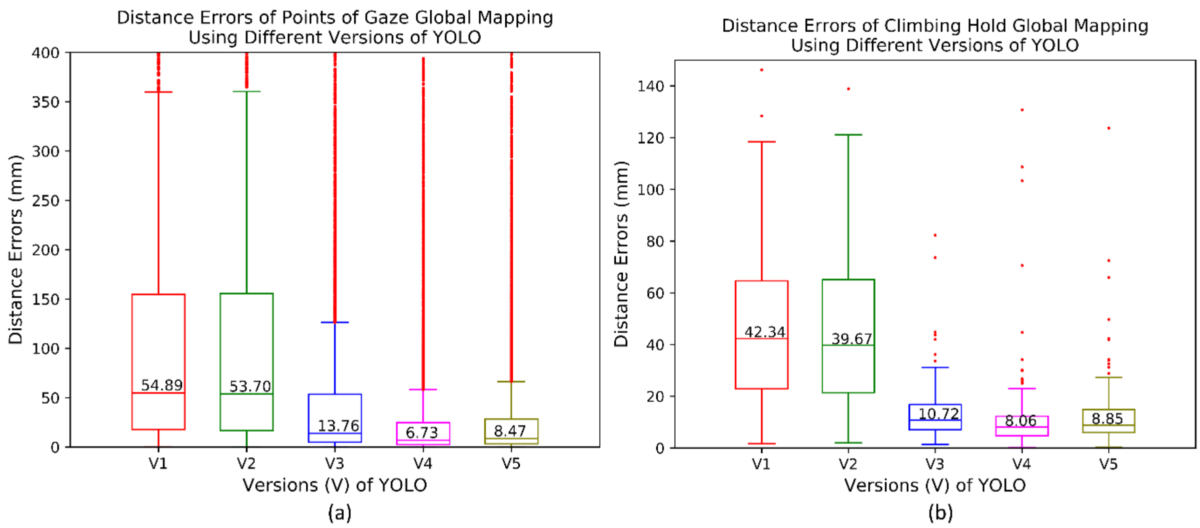

Figure 11. *Distance errors of (a) points of gaze global mapping and (b) climbing hold global mapping with different versions (Vs) of YOLO (V1, V2, V3, V4, and V5) using the separate training strategy in the CNN-based POG and CH global mapping. Median values are noted inside the boxplots. Median values are reported in the box plots.*

With the optimal POG and CH global mapping method, the whole 2,640 climbing video cases were processed automatically frame-by-frame and case-by-case. The description of the processed datasets is described in Section III.4 of this report. The copies of those processed datasets and their instructions were transferred to the Roue University, France. Moreover, they can also be downloaded via the link: https://drive.google.com/drive/folders/1_cnYGznhgZyrwSjtztoz7X6WIzYtoBcs?usp=sharing. The dataset tutorials could also be downloaded via the link: https://www.dropbox.com/scl/fo/3g417imkebusni84if4hc/h?dl=0&rlkey=v0dfnz973oi6klr9mua9t3l72.

V. Impact socio-économique et sociétal :

Gaze behaviors are important to sport-climbing both before and during the climbs. To study these effects of gaze behaviors, a large dataset should be generated. Currently, no studies have tried to acquire and process these types of datasets, especially in an automatic manner. During more than 10 months of post-doctoral research, we have accomplished three main contributions. First, a novel software for post-processing climbing video cases from raw datasets acquired by the Tobii Pro Glasses 2 was developed as the first version. By using this software, we do not have to use the software Tobii Pro Lab from Tobii Pro Group [28]. This will save the budget for licenses. Second, we developed an automatic and robust POG and CH global mapping for computing the global positions of POGs and CHs on the global climbing walls. These methods were reported in two ongoing articles. Third, using the optimal global mapping method, all processed datasets including 2,640 climbing cases are available for analyzing the effects of gaze behaviors on climbing performances. The processed datasets are transferred currently used by the Rouen University, France.

In perspective, we are preparing the second manuscript relating to the CNN-based POG and CH global mapping method. Moreover, the second version of the software will be updated for automatically computing the POGs and CHs after cutting a climbing case. More functions, such as fixation point computing and climbing performance analyses will also be added in the next versions of the software.

VI. References

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