Enhancing Speed Climbing Performance and Optimizing Training Methods Through Advanced Video Analysis

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Abstract: This paper presents the implementation of an automated recording and analysis system for the capturing and evaluation of performances of speed climbing athletes. In collaboration with the National Youth Sports Institute (NYSI) in Singapore, an advanced camera system was installed on a newly constructed speed climbing wall, aiming to enhance training protocols by providing detailed performance insights. The paper is mainly split into two parts: the first one describes the hardware setup, including camera selection, configuration, integration with the existing infrastructure and data collection methods. The second part presents the analysis of performance data of one athlete trained at the NYSI, highlighting key findings and potential training improvements. Preliminary results indicate significant benefits in technique refinement and performance optimization, demonstrating the system's value in a competitive training environment. Through section wise analysis of several runs of the same athlete, a stagnation in the start section of the standardised wall has been detected. However, a significant improvement was determined in the other sections, which led to a noticeable overall increase in performance in less than 2 years of regular training.

1 INTRODUCTION

Climbing as a sport is experiencing rapid growth. The International Federation of Sport Climbing (IFSC) reports that approximately 25 million people of all ages now climb regularly around the world. Between 2001 and 2012, the global number of climbers and climbing facilities surged by nearly 50% (Grønhaug and Norberg, 2016). The sport has also gained greater recognition in the media, and the number of newly built climbing centers continues to rise, reflecting its increasing popularity. The acknowledgment on an international level is also remarkable, especially with its debut as an Olympic discipline at the 2020 Tokyo Olympics and its continued presence in the recently concluded 2024 Olympics in Paris. Whereas in Tokyo all three disciplines Bouldering, Lead and Speed Climbing were combined within one competition, this mode has changed in Paris with the separation of speed climbing as an independent discipline. These disciplines differ in terms of execution and loading, as highlighted by (Winkler et al., 2022), as well as the power demands of the upper limbs, emphasized by (Levernier et al., 2020). Despite these differences, the results in Speed Climbing for both men and women in Paris showed significant improvements compared to Tokyo. For example, the previous Olympic record improved from 6.97s to 6.06s for women and from 5.45s to 4.74s for men (International Federation of Sport Climbing, 2024). This success was unexpected, considering the stagnation of top-end times in the years following Tokyo. This breakthrough shifted the focus to refining technique and optimizing performance, especially for young athletes aiming to compete at the highest levels.

Speed Climbing continues to evolve in various ways: athletes are shortening the climbing route by skipping certain holds (Pandurević et al., 2022) and optimizing the starting position to enhance their effi-

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ciency. Similar adjustments are also being made in the final phase of the climb, which helps reduce time and improve overall performance. These innovations are driving the dynamic progression of the discipline. As Speed Climbing advances, the technology used to train the next generation of athletes must keep pace with these changes.

This study is based on the collaboration with the National Youth Sports Institute (NYSI) in Singapore, an institution dedicated to the development of youth athletes across various sport disciplines. Utilization of NYSI's modern facilities including a newly established standardized speed climbing wall, an automated camera system was designed and implemented to provide detailed insights into climbing performance. Accordingly, this paper is structured in two parts, namely

- the design and implementation of a robust camera system capable of recording speed climbing videos with little effort and
- the evaluation of recorded data to identify patterns and insights for the enhancement of training methods for speed climbing athletes.

The hardware was designed with mobility and simplicity in mind, so that the system can be used flexibly depending on the application. Since the athletes and trainers should concentrate on the sport itself, the system is intended to reduce the effort involved in recording and subsequent video analysis.

There are already several research groups working on similar topics related to the performance analysis in sport climbing. Besides several approaches focusing on the usage of embedded climbing holds with a wide variety of instrumentation solutions, there are also some methods presented on how to track the body of sport climbers in different ways. Most common is the application of markers on several positions on the body (Reveret et al., 2020). Using a drone-based system tracking a marker placed on the harness of the speed climbing athlete, this approach enables the determination of the body's 3D position and velocity. Compared to that, (Beltrán et al., 2022) presented a method for the segmentation of human body movements in sport climbing using kinematic variables obtained from RGB-D cameras, combining the rendered RGB images using different pose estimators with the aligned depth frames. Legreneur et al., as one of the first, (Legreneur et al., 2019) manually analyzed speed climbing runs of athletes participating at the Youth Olympics 2018 using the open-source video analysis tool Kinovea. This approach was further developed in (Elias et al., 2021) creating a data set of 362 speed climbing runs including 55 world elite climbers with the help of the human pose estimator OpenPose (Cao et al., 2018).

Similarly automated movement analysis are also carried out in other sports. (Evans et al., 2021) presents two methods for precisely measuring sprinter's foot-ground contact locations and timing using multi-camera systems, where one of the presented approaches relies on machine learning-based human pose estimation using OpenPose.

This research aims to contribute to the field of sport science by demonstrating the practical application of video analysis technology in speed climbing. It should offer valuable insights into performance analysis and possibilities for the optimization of training methods to keep up with the rapid growth of this Olympic discipline. The surprising surge in performance observed at the Olympic Games in Paris 2024 highlights the importance of continuous investigation and improvement of existing training methods and the replacement of commonly used manual and time-consuming video analysis with automated systems based on neural networks. The presented results reflect the need for such systems and demonstrate the relevance of this research.

2 METHODOLOGY

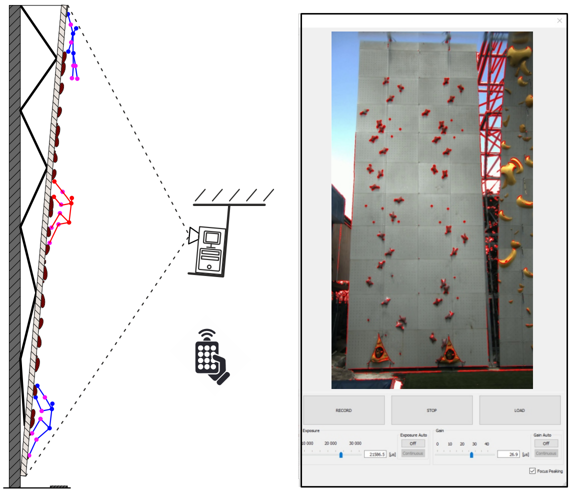
As already mentioned, this paper is firstly based on the design and implementation of a hardware system for the automated recording and analysis of speed climbing videos.

Figure 1 roughly summarizes the implemented camera system consisting of a remote-controlled recording unit and a synchronized user interface (UI) running on the related computer with live preview of the camera output and several functionalities for the adjustment of the scene. Apart from starting, stopping and initiating the upload to a cloud via remote or UI control, the workflow from recording to receiving extensive data packages is fully automated.

2.1 Camera System Design

2.1.1 Housing

In order to accommodate the entire measurement system consisting of computer, camera and power supply units in one compact housing, a chassis with the dimensions 239 x 300 x 160 mm with a transparent lid was chosen. Particular emphasis was placed on the usage in outdoor areas with a sealed closure capability. Due to the specific climate in Singapore and the associated high humidity, the entry of humid air



(a) (b)

Figure 1: Illustration of the camera system with (a) Side view of the speed climbing wall and visualization of the remote-controlled camera setup and (b) the programmed user interface with snapshot of the camera recording with enabled focus peaking function.

into the interior of the housing must be prevented, as this could cause damage to the built-in electronics. In order to be able to cool the heating measurement system properly, a fan was installed on the underside, whereby the air can circulate from the inside to outside through two holes covered by ventilation grilles.

2.1.2 Processor

For controlling the camera, receiving and processing signals from the remote control and uploading recorded speed climbing runs to the configured cloud, an Intel i5 NUC 11 Pro Kit with 16 Gb memory is installed. Its compact size of 117 x 112 x 37 mm ensures an easy installation in the housing with comparatively high performance output. An additional 8” touchscreen monitor from Magedok has been installed for troubleshooting and obtaining feedback. Moreover, it allows manual operation of the programmed UI on a 720p display if the remote control should fail.

2.1.3 Sensor and Lens

The choice of an appropriate camera was again based on both compact size as well as performance/usability. In order to obtain high-quality results from the backend system, at least HD quality (1080p) and 30 FPS are required for recordings in vertical format (recording of the entire speed climbing wall, see Figure 1b). The industrial USB camera Alvium 1800 U-511C manufactured by Allied Vision fulfills all these minimum requirements and, with a size of 29 x 29 x 38 mm, fits well into the overall system. The compatible LMVZ4411 lens from Kowa completes the camera unit offering manual focus and zoom adjustment with a focal length range of 4.4 - 11 mm.

2.1.4 Remote Control

The camera setup is completed with the implementation of a wireless remote system for controlling the recording and upload processes. To protect the built-in electronics from impact and aforementioned humidity, a sealed hand-held housing (165 x 90 x 34 mm) has been selected. It can store both an ESP32 Feather V2 Adafruit microcontroller with associated circuit board and a LiPo battery pack with 6600 mA h capacity. In addition, 3 push buttons with built-in led indicators for start, stop and upload functionality as well as a led light for monitoring the battery charge status were installed on the lid of the housing. The remote control was designed to enhance the usability of the system during training sessions, minimizing the need for direct interaction with the camera hardware.

2.1.5 User Interface

The programmed UI provides direct control over the camera with buttons for starting, stopping and uploading, enabling operations without the need for the remote control. It features a live preview of the camera output and is synchronized with remote to ensure that triggered actions are mirrored in the interface. In addition, the interface includes modifiers like sliders and buttons for the adjustment of exposure and gain parameters of the camera (see Figure 1b). Users can disable the, by default set, continuous automatic adjustment by the camera, or manually set these parameters with a defined range for precise control over the recording settings. To adjust the focus of the camera using the mechanical controls on the camera, a focus peaking function can be enabled, which highlights sharp edges with red lines on the recording and thus supports this manual adjustment.

2.2 Integrated Control System

This subsection introduced the developed control system to manage the recording and data management processes. Thereby, the system consists of both the mentioned wireless remote control powered by an Arduino device and a Python-based UI for manual operation and troubleshooting.

2.2.1 Arduino-Controlled Remote System

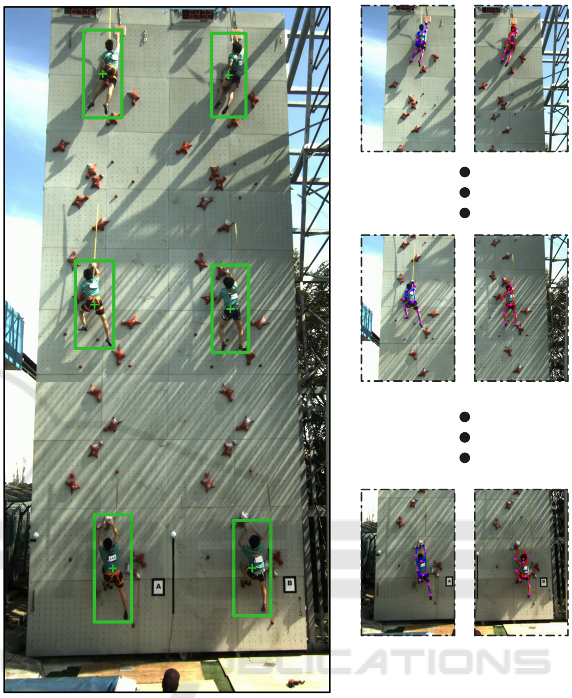
The Arduino microcontroller forms the core of the remote system and allows users to start, stop and upload recordings remotely. This system uses WiFi communication to interact with the camera setup, whereby the microcontroller initially connects to the computer via provided mobile hotspot. This allows the recording process to be both efficient and user-friendly. The data transfer is realized using MQTT (Message Queuing Telemetry Transport). MQTT is a lightweight messaging protocol based on a publish-subscribe approach. Its application area designed for low-bandwidth, high-latency networks is ideally suited for this control system. Devices (clients) publish messages to defined topics on a broker (server), which then distributes theses messages to all subscribed clients, enabling efficient, real-time data exchange.

The main tasks of the microcontroller is the establishment of a connection with the computer and the management of publish and subscribe topics for the processing of trigger signals of the push buttons. In the Arduino code, actions for sending messages for start, stop or upload are triggered with related topics when the corresponding push buttons are pressed. For manual execution via UI, subscribe topics are defined to synchronize the Arduino and the computer, ensuring both devices stay in sync for the same actions. In addition, a publish topic is specified, defining the battery charge status of the installed LiPo.

2.2.2 Signal Processing and Direct Camera Control

On the computer of the camera system, a python script is executed, which mainly handles receiving and processing signals from the remote control, managing the camera through Vimba library, capturing frames and processing them into a suitable video. Additionally, the script runs the mentioned UI, set up for direct camera control in case of remote control failure or for camera setup testing. A focus peaking function has also been implemented to support the manual adjustment of the lens using the mechanical controls on the camera (zoom and focus) setting optimal focus. This function highlights areas of the image that are in sharp focus by detecting edges via Canny detector and overlaying a red color filter (see Figure 1b). Therefore, the focus is optimally adjusted when the whole image or areas of interest have the most distinctive and extensive highlights.

As already mentioned, the Arduino and Python components are both designed to work in tandem, providing a robust and flexible control system for the recording of speed climbing recordings. While the Arduino programmed remote offers fast and effortless operation provided primarily for trainers, the Python UI enables precise adjustment of camera settings and diagnostic tasks can be handled effectively. This dual-system approach increases the reliability and versatility of the control unit and ensures continuous operation during speed climbing runs.



(a) (b)

Figure 2: Summary of the image processing from capturing athletes on both sides of the speed climbing wall to cropped images for further processing; (a) Overlaid images of two athletes at different heights on the speed climbing wall tracked with MMDet (Chen et al., 2019); (b) Resulting crop of the recordings to isolate both athletes for the subsequent human pose estimation with MMPose (Contributors, 2020).

2.3 Backend System for Human Pose Estimation and Feature Detection

Once a video of a speed climbing run has been recorded with the described camera system, this output requires post-processing to enable further analysis. In order to achieve equivalent results in each area of the climbing wall regardless of the height, the recording is cropped such that the respective athlete is focused on both sides (see Figure 2b). To achieve this, the application MMDetection (Chen et al., 2019) is required first. This powerful framework is commonly used to detect humans as objects in images by applying models pre-trained on large datasets like COCO (Lin et al., 2015). By the detecting the human body of both athletes and marking them with surrounding rectangles (see Figure 2a), the resulting cropped images are a result of moving a window over the whole route map aligned at the height of the rectangles' center. Furthermore, the two sides of the speed climbing wall are split by detecting climbing holds and determining the dividing line. By using the object detector YOLO and a self-trained model, the holds placed furthest to the left and right are first determined in order to calculate the edges as well as the center line of the entire speed climbing wall. By combing the cropped images, a video is created which follows the athlete for each side similar to camera-guided recordings. This inevitably leads to a reduction of the resolution from 1920x1080 px to 720x1280 px for each frame, whereby the remaining width of 200 px is supplemented by adding black bars on both sides of each image.

By using the top-down approach for human pose estimation consisting of MMDetection and MMPose (Contributors, 2020) as well as other feature detectors described in (Pandurević et al., 2022), movement related parameters may be calculated. The previous step eliminates thereby the need for renewed detection human body surrounding rectangles using MMDetection. In addition, the calculation step of detecting and matching random feature points in each image to estimate the absolute camera movement is skipped, as this vector has already been determined for both sides by the defined window movement within the cropping process.

The described backend processes run on a external server with a powerful processor and graphics card to ensure rapid calculations of the data for an immediate feedback for the trainers and athletes. Finally, the analyzed data packages are transferred to the same cloud system used for uploading the recordings, which can then be evaluated using the provided analysis software.

2.4 Analysis Tool

Along with the designed camera system, the NYSI was provided with an analysis tool for the visualization of the calculated data sets (see Figure 3). Due to the extensive range of computable parameters by the backend system, the data sets are broken down to the most critical metrics. The software enables the comparison of joint angles and velocities, as well as position, velocity and acceleration of the center of gravity (COG). For better understanding and correlation with the data, each data point can be linked to the corresponding image of the athlete with overlaid body skeleton. In addition to the mentioned data plots, a visualization of the route map with the path of the COG is also provided. By clicking on the visualized climbing holds, the jumping to specific positions in the data set is enabled, allowing the synchronization of athletes at different heights for a detailed analysis of certain sections on the speed climbing wall. The software allows the comparison of up to two athletes simultaneously from one or different recordings.

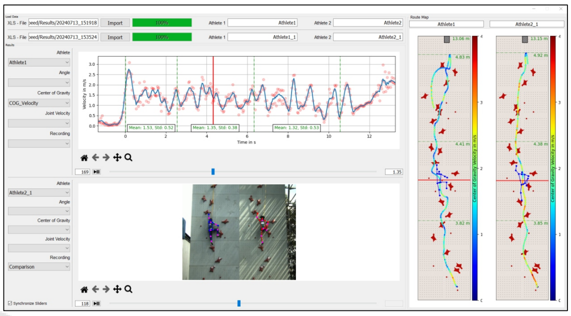


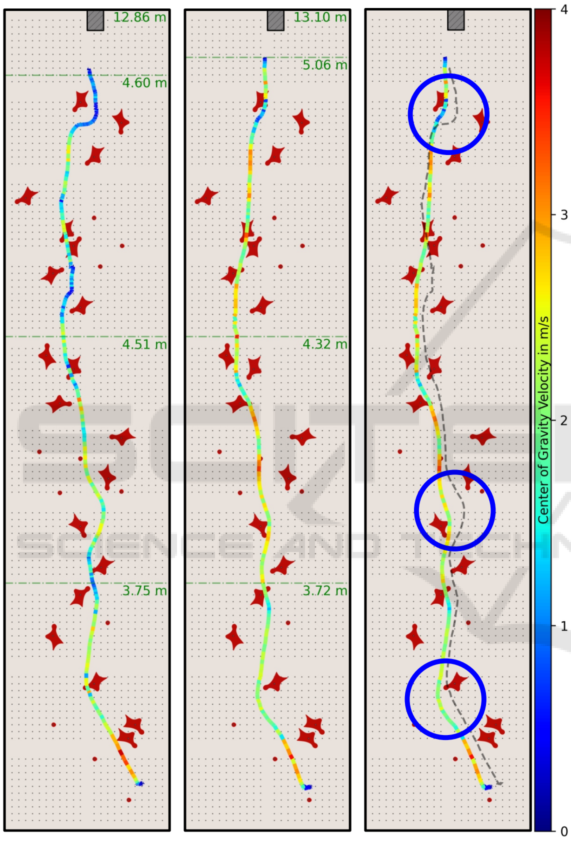
Figure 3: Representation of the analysis tool with visualization of the data sets of two athletes from different recordings.

3 RESULTS

To validate the above described measurement system, recorded data sets over 1.5 years were analyzed. Various parameters were extracted and the progression of the performance was evaluated. Table 1 displays an outtake of the statistical analysis of several biomechanical parameters of a speed climbing athlete, with data collected at the NYSI in two different periods: March 2023 and July 2024. The 23 year old athlete has been trained at the NYSI since his youth and continues to do so due to his potential. The analysis focuses on various performance indicators, namely end time, velocity, path length, limb frequencies and contact times. Due to their importance and influence, the velocity and path data were considered in even further detail by additionally evaluating the individual sections of the speed climbing wall (start, middle, end). Thereby, the start section covering the first 5 holds of the speed climbing wall, the middle section holds 6 to 12 and the end section the remaining ones. For the frequencies and contact times, the values for hands and feet have been combined.

Starting with the most informative parameter, the end time ranged at the beginning of our measurement time period in March 2023 from a minimum of 6.77 s to a maximum of 8.53 s, with an average of 7.32 s. Compared to that, by July 2024, the end time showed a significant improvement, varying around an average of 5.99s, reflecting a reduction of 18.09 %, indicating a remarkable increase in performance.

The velocity experienced a slight decrease in the starting section of the route map, dropping from an average of 2.19 m/s in March 2023 to 2.18 m/s. However, this parameter increased significantly in the middle and end section and thus also in the entire area of the wall. In terms of numbers, the velocity increased by an average of 18.51 % in the middle section, 41.77 % in the end section and 25.13 % over the entire movement process.



(a) (b) (c)

Figure 4: Comparison of the route map (position and velocity of the COG) of the same athlete with section-wise and overall path lengths measured in March 2023 (a) and July 2024 (b); (c) shows the overlay of both route maps with blue circles marking points of significant change in technique.

Figure 4a and 4b each show one run from the data sets measured in March 2023 and July 2024. Despite relatively small reduction in path length in the start and middle sections (see Table 1), Figure 4c indicates an obvious improvement in motion sequences in all wall sections. However, particularly striking in the statistical analysis is the almost unchanging overall path length by 0.03 %. Since the calculated path length in the end area includes the positions up to the top buzzer, the athlete was aiming for different end positions on these two days. When comparing the video footage, it is noticeable that on training days in March 2023 no end buzzer was mounted and the athlete's last jump thus did not turn out high enough.

The analysis of the limb frequencies reveals both an increase and a decrease. While the frequency of the feet reflects an improvement of 12.05 % and thus a significant increase in performance, the average value of the hands falls from 1.84 Hz to 1.56 Hz and in relative terms by 15.50 %. This indicates a shift in the athlete's technique, whereby the movement of the feet became faster, while the hands slowed down conspicuously.

Finally, it should be emphasized that the contact times between hands and feet also varied considerably. There was a significant decrease of 21.21 % for the hands and 13.58 % for the feet, indicating a more efficient and faster climbing technique.

4 DISCUSSION

The analysis of the speed climbing athlete's performance, including the data from Table 1 between March 2023 and July 2024 reveals several critical insights into his performance. The individual results of the measured parameters are discussed in more detail in the following subsections. Lastly, the limitation of the measurement system are described.

4.1 Velocity

The almost constant velocity with a slight decrease recorded at the end of the measurement period (-0.56 %) may not be indicative of a true performance decline. This change could be attributed to daily fluctuations in the athlete's physical state. This stagnation indicates that the training focus was placed on other wall sections and no further improvement of the start technique was achieved. However, the athlete was able to compensate this with significant increases in the middle and end section, where velocity jumped by 18.51 % and 41.77 %, respectively. The overall improvement from 1.63 m/s to 2.04 m/s, refers to enhanced efficiency and power as the athletes progresses on the wall.

4.2 Path Length

The slight increase in path length, particularly noticeable in the end section, is mainly attributed to a

Table 1: Summary of the descriptive statistical evaluation of a NYSI athlete in the period from March 2023 to July 2024. In addition to the values for minimum (Min), maximum (Max), median (Avg) and standard deviation (Std), the relative change of the average values in % is also provided.

		Time in s	Velocity in m/s				Path Length in m				Frequency in Hz		Contacts in s	
	Statistics	End Time	Start	Middle	End	Total	Start	Middle	End	Total	Hands	Feet	Hands	Feet
March 2023	Min	6.77	2.11	1.81	1.20	1.53	3.44	4.42	4.39	12.45	1.70	0.93	0.52	0.43
	Max	8.53	2.27	2.03	1.70	1.77	3.83	4.56	4.54	12.80	2.13	1.05	0.77	0.53
	Avg	7.32	2.19	1.93	1.49	1.63	3.74	4.51	4.48	12.71	1.84	0.98	0.55	0.44
	Std	0.49	0.05	0.06	0.15	0.09	0.12	0.04	0.05	0.10	0.13	0.04	0.09	0.04
July 2024	Min	5.97	2.16	2.25	2.10	1.98	3.70	4.39	4.48	12.70	1.50	1.10	0.40	0.38
	Max	6.02	2.20	2.33	2.11	2.10	3.72	4.54	4.59	12.72	1.61	1.11	0.47	0.39
	Avg	5.99	2.18	2.29	2.11	2.04	3.71	4.47	4.53	12.71	1.56	1.10	0.43	0.38
	Std	0.03	0.02	0.04	0.01	0.06	0.01	0.07	0.07	0.05	0.05	0.01	0.03	0.01
Relative Change in %		-18.09	-0.56	18.51	41.77	25.13	-0.85	-0.83	1.22	0.03	-15.50	12.05	-21.21	-13.58

change in sensor placement in training to comply with IFSC regulations. This adjustment likely extended the measured path length at the end of the runs recorded in July 2024. While the increase in path could theoretically challenge the athlete's velocity, the simultaneous reduction of the end time suggests that the athlete has adapted to this change effectively. Nevertheless, future training sessions should be standardized to ensure data comparability.

4.3 Limb Frequency and Contact Time

Thereby, the most pronounced improvement was measured by the limb frequency of the feet, which increased by 12.05 %. This enhancement is crucial for the reduction of contact times, a key factor not only in speed climbing but also in sprinting. The decrease of frequency of the hands could indicate a shift towards more intentional and efficient hand placement, reducing unnecessary movements and optimizing the athlete's run.

Getting back to sprinting, the ground contact time (GCT) is a critical factor for the evaluation of performance. Studies by Hunter et al. (Hunter et al., 2004) and Mero et al. (Mero et al., 1992) reveal that elite sprinters have shorter GCTs, enabling maximal force generation and rapid transitions between single steps. Similarly in speed climbing, the reduced contact times for both hands (-21.21 %) and feet (-13.58 %) indicate less time in contact with the climbing wall, which in turn is directly related to an increase in velocity.

The concept of vertical ground reaction force (GRF) (Hunter et al., 2005) is likewise relevant. While faster sprinters generate a comparable vertical GRF to slower sprinters, they achieve this in a shorter GCT (Weyand et al., 2000), resulting in a longer step length and a higher horizontal velocity. The athlete's increased feet frequency and reduced contact times mirror this principle, pointing out a more efficient transfer of force and faster transition between movements.

4.4 System Limitation

Although the measurement system was designed to be mostly automated, manual readjustments of the camera must be carried out before each measurement session. Therefore, the camera has to be set using the two parameters exposure and gain, and the focus of the lens needs to be adjusted. Furthermore, in the future, an improvement of the camera could aim for higher resolutions and frame rates. Currently, recordings are limited to a maximum of 1080p in order to maintain 30 FPS. After cropping the single frames as explained in Figure 2, only a maximum of 640 x 720 px remains to detect each athlete and various features in the image.

5 CONCLUSION

The introduced measurement system enables trainers and athletes at the NYSI to monitor relevant movement parameters and their evaluation in single wall sections to optimize individual training methods. The user-friendly handling of the wireless camera system ensures the recording and calculation of the data in real time and its visualization using the provided analysis software. By using this system since its introduction in March 2023, several data packages from different athletes have already been calculated. The results of one of these promising athletes still training at the NYSI were presented in this study. The improvements observed, especially in the middle and end section of the speed climbing wall, highlight the athlete's positive adaptation to training methods and enhanced techniques. The conspicuous reduction in end time and improvement in most of the presented parameters confirms this overall improvement from March 2023 to July 2024. Nonetheless, motion sequences, especially in the start section should be examined in more detail and training methods should be adapted accordingly in order to achieve an additional increase in performance. The slight increase in path length, influenced by methodological changes, underscores the need for consistent measurement practices in future recordings and analysis.

Despite the fully automated process from recording the speed climbing run to displaying the data, it takes a qualified person who either brings extensive experience in this sport and/or has a sport scientific background to be able to efficiently draw conclusions about errors in movement and performance evaluation. The involvement of a sports scientist, particularly one specialized in applied biomechanics, would be crucial. Such an expert would collaborate with the coach responsible for the athlete's technical preparation, as well as with the strength and conditioning trainer. For both coaches, the data would provide valuable insights for refining and optimizing training programs, which would ultimately lead to an improvement of performance in all sections of the wall.

For future projects, we want to maintain the collaboration with the NYSI in order to follow the development of young athletes and to gain further insights into the performance of speed climbing athletes by expanding the data sets and improving the measurement system.

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