

USE OF VIRTUAL REALITY TECHNOLOGY FOR TRAINING STANDING SHOOTING, POSTURAL BALANCE, AND RIFLE STABILITY IN BIATHLON: A PILOT STUDY

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Использование технологии виртуальной реальности для обучения стрельбе стоя, постуральному балансу и стабильности ружья в биатлоне: пилотное исследование

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Abstract

Success in biathlon depends on physical fitness, psychophysiological parameters, and biomechanics. Key aspects include the speed and accuracy of shooting, which affect body oscillations and the stability of the "body-rifle" system. The level of stress, environmental conditions, and ski preparation are also important. This study is aimed to provide a thorough theoretical analysis of the factors affecting the standing shooting performance in biathlon, and to conduct a pilot study using VR to validate it as a training tool based on the

Резюме

Успех в биатлоне зависит от физической подготовки, психофизиологических параметров и биомеханики. Ключевые аспекты включают скорость и точность стрельбы, которые влияют на колебания тела и стабильность системы «тело-винтовка». Также важны уровень стресса, условия окружающей среды и подготовка лыж. Целями данного исследования являются тщательный теоретический анализ факторов, влияющих на показатели стрельбы стоя в биатлоне, и проведение пилотного исследования с использованием VR для проверки его в качестве тренировочного инструмента на

The work was carried out within the framework of the Laboratory of Convergent Studies of Cognitive Processes of the Federal Scientific Center for Psychological and Interdisciplinary Research, established within the framework of the competition of the Ministry of Education and Science of Russian Federation.

Работа выполнена в лаборатории конвергентных исследований когнитивных процессов Федерального научного центра психологических и междисциплинарных исследований, созданной в рамках конкурса Минобрнауки России.

observed parameters. This study utilized the Biathlon-2024 Virtual Environment, which simulated skiing and standing shooting in classical biathlon. This Virtual Environment is developed on Unity 3D platform and includes two stages: 1) VR skiing, 2) shooting. Subjects performed shooting at virtual targets, whereby the VR visualization fully simulated a biathlon shooting range. The results confirmed that stability of body-rifle system is crucial for successful shooting in biathlon. It was observed that elite athletes demonstrate a better postural balance and a lower sway compared to beginners. The data analysis obtained with Antilatency system trackers showed a distinct correlation between the limb and rifle positions, which highlights the importance of a fine postural control and reaction time when shooting. The study emphasizes that success in biathlon depends not only on physical fitness and shooting techniques, but also on environment, psychophysiology, and individual attributes such as tremor. This therefore makes an integrated approach to athlete training essential for high performance.

Keywords: biathlon, standing shooting, psychophysiology, success factors, biomechanics, tremor.

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основе наблюдаемых параметров. В данном исследовании использовалась виртуальная среда «Биатлон-2024», которая имитировала лыжные гонки и стрельбу стоя в классическом биатлоне. Эта виртуальная среда разработана на платформе Unity 3D и включает в себя два этапа: 1) лыжи VR, 2) стрельба. Испытуемые выполняли стрельбу по виртуальным мишеням, при этом VR-визуализация полностью имитировала биатлонное стрельбище. Результаты подтвердили, что стабильность системы «тело-винтовка» имеет решающее значение для успешной стрельбы в биатлоне. Было замечено, что элитные спортсмены демонстрируют лучший постуральный баланс и меньшее раскачивание по сравнению с новичками. Анализ данных, полученных с помощью трекеров системы Antilatency, показал четкую корреляцию между положением конечностей и винтовки, что указывает на важность тонкого постурального контроля и времени реакции при стрельбе. Данное исследование подчеркивает, что успех в биатлоне зависит не только от физической подготовки и техники стрельбы, но и от окружающей среды, психофизиологии и индивидуальных особенностей, таких как тремор. Поэтому для достижения высоких результатов необходим комплексный подход к подготовке спортсменов.

Ключевые слова: биатлон, стрельба в положении стоя, психофизиология, факторы успеха, биомеханика, тремор.

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Acknowledgements

The authors are grateful to coaches and athletes for their assistance in conducting the research.

Благодарности

Авторы статьи выражают благодарность тренерам и спортсменам за помощь в проведении исследования.

Biathlon is an Olympic sport that uniquely combines skiing and rifle shooting in a high-stress environment that requires extensive physiological effort along with fine motor control that is necessary for efficient shooting (Laaksonen et al., 2018). There are very few scientific studies on performance-related factors in biathlon standing shooting. This is particularly due to how challenging they are to investigate: firstly, this phenomenon is complex on different levels (biomechanics and postural control, psychophysiological parameters, physiology, psychological factors) (Mikhalev et al., 2014; Sattlecker et al., 2014); and secondly, there are many extra variables, such as stress levels (Abrahamsen et al., 2024; Finkenzeller et al., 2016; Heinrich et al., 2021), environment (temperature and altitude of the venue) (Skattebo & Losnegard, 2018), preparation of skis and ski trail (Losnegard et al., 2011; Rønnestad et al., 2016; Sandbakk et al., 2011, 2013).

The speed and accuracy of shooting are two critical performance parameters in biathlon that are significantly affected by body sway, stability of the body-rifle system, rifle butt pressure (Ivanov et al., 2022), and trigger pull behavior (Galay et al., 2021). Moreover, the physical exercise prior to shooting clearly modifies psychophysiological processes related to the complex task of aiming (Hoffman & Street, 1992; Luchsinger et al., 2019).

Shooting can also be impacted by the race format. Thus, for instance, the result in sprint may be 60% dependent on ski speed, while in individual races, where time is added for missed shots, the shooting performance has more value (Luchsinger et al., 2018).

Therefore, it is obvious that many factors contribute to success in biathlon. The gap between existing research and the expected outcomes of new studies in biathlon lies in the insufficient exploration of factors affecting standing shooting. The existing studies do not address the complexity of the interactions between biomechanical, physiological, and psychological factors, as well as variables like stress

levels and environmental conditions. To study them more effectively, one can use such technologies as virtual reality (VR) that allow simulations of various conditions (Polikanova et al., 2022a, 2024; Yakushina et al., 2024; Gasanov et al., 2025) and register a combination of psychophysiological, biomechanical and sensory-motor parameters in parallel (Polikanova et al., 2022b; Leonov et al., 2020).

This study is aimed to provide a thorough theoretical analysis of the factors affecting the standing shooting performance in biathlon, and to conduct a pilot study using VR to validate it as a training tool based on the observed parameters.

Study of Athletes' Standing and Balance

Static balance substantially affects sport results and is one of the key factors that affect athlete performance. When assessing postural control, center-of-pressure (COP) is usually registered (Michalska et al., 2022).

Several studies have shown that athletes are remarkably better at holding static postural balance compared to non-athletes. This is particularly evident when the task complexity is increased, e.g., when changing the inclination of a special platform (stabilometry) (Thompson et al., 2017; Sadowska et al., 2019a; Michalska et al., 2022), or when eyes are closed (Sadowska et al., 2019b).

Biathlon shooting is an extremely complex motor activity that requires good posture stability, rapid motor task execution and fine motor control under high psychological pressure. However, the skills involved in prone and standing shooting are not the same (Gros Lambert et al., 2007).

In prone shooting, the rifle stability is improved due to the shooting strap (Ibid.). In standing shooting, the body-rifle system stability is a critical variable that both elite shooters (Era et al., 1996; Lakie, 2010) and elite biathletes (Niinimaa & McAvoy, 1983) are characterized by. Based on some reports, the aiming strategies of shooters and biathletes are considerably dissimilar (Larue et al., 1989). Shooters attempt to control body and rifle sway, while biathletes rely on matching anticipation strategies. Multiple studies find that professional biathletes swing less compared to novices, including after a simulated physical activity (Ihalainen et al., 2018; Lang & Zhou, 2022; Sadowska et al., 2019a; Sattlecker et al., 2014). Meanwhile, anteroposterior movement is a greater contributor to sway than the lateral one (Niinimaa & McAvoy, 1983; Sattlecker et al., 2014).

Factors Affecting Tremor During Shooting

Tremor obviously plays an important role in shooting efficiency. Hence, the factors that affect the tremor magnitude are expected to influence shooting performance. There is some supportive evidence for mechanical, reflectory, and central mechanisms that trigger tremor, and it is probable that all of them may contribute to some extent (Durbaba et al., 2005; Lakie et al., 1986; McAuley et al., 2000). Generally, scientists agree that tremor control is beyond the power of will.

Tremor magnitude may change due to neurogenic or myogenic causes. Alcohol, for example, is known to reduce the sizes of essential tremor and physiologic tremor

(Growdon et al., 1975; Lakie et al., 1994a; Landauer, 1981). Lowering the limb temperature, for example by immersing it in cool water through myogenic action, also reduces muscle tremor. The exact opposite is seen with the limb warming (Lakie, 2010; Lakie et al., 1994b), as well as with β 2-agonists such as adrenaline (Marsden & Meadows, 1970). Presumably this is why physical activity causes tremor increase, which is observed not immediately, but approximately 5-10 minutes after the concentration of β -agonists in the bloodstream reaches its peak (Lakie et al., 2003). Exhausting limb physical exercise can also cause a specific tremor increase. Therefore, people who are planning to do fine work avoid prior intense physical activity for around a day (Furness et al., 1977).

Another factor that affects the magnitude of tremor is cardiac activity and, to a certain degree, respiratory movements (Žák & Ondráček, 2021). With each heartbeat, a limb transiently vibrates, supposedly at its resonant frequency. Its magnitude is likely to represent only 2–10% of the total postural tremor (Marsden et al., 1969).

We thus see that postural balance plays a pivotal role in biathletes' performance, ensuring high stability of the body-rifle system and, therefore, shooting accuracy. Meanwhile, athletes show better static balance compared to non-athletes, especially under challenging conditions. Intense physical activity can have a negative effect on rifle grip stability and reaction time. Tremor has a significant impact on shooting performance, and its magnitude depends on multiple factors, including neurogenic and myogenic mechanisms. All the above highlights the significance of both physical and motor training in achieving success in biathlon.

Methods

Biathlon-2024 Virtual Environment

This study utilized the Biathlon-2024 Virtual Environment, which simulated skiing and standing shooting in classical biathlon. A detailed description of the Biathlon-2024 Virtual Environment and its technical characteristics are presented in Gasanov et al., 2025.

This Virtual Environment is developed on Unity 3D platform and includes two stages: 1) VR skiing, 2) shooting. Subjects performed shooting at virtual targets, whereby the VR visualization fully simulated a biathlon shooting range (Figure 1). Figure 2 shows the view types of subjects.

To simulate shooting in a virtual environment, the Pioneer 345K rifle was used without the gas block required for firing. It served as a model identical to real conditions, as even a slight change in the weight of the weapon is critical for the shooting efficiency of professional athletes. In our case, shooting is performed in a VR environment by pressing a button located under the trigger (Figure 2). The use of the Pioneer 345K rifle is essential for accurately simulating the trigger pull, which athletes consider important in biathlon. When the trigger is pulled in a virtual environment, a shot is fired, and a hit is counted if the rifle is aimed at the target.

Figure 1

Virtual Environment Simulation of Shooting at Biathlon Targets (Subject View)



Figure 2

Subjects During Shooting (Left and Center); Trigger and Trigger Switch Location on the Test Rifle (Right)



Each subject had eight rounds for five targets and the opportunity to adjust their aim (Figure 3). VR environment allowed modifying the distance to the targets, which in biathlon amounts to 50 meters. However, due to limitations of some helmets and in order to train beginners, in the first stages, we decided to reduce the distance to 20–30 m.

Rifle Tracking System

A key VR element was a tracking system implemented via Antilatency¹ system. Figure 2 provides an illustration of how the Antilatency sensors were placed on the

¹ <https://antilatency.com/>

Figure 3

Advanced Operator Interface



subjects' bodies. This equipment included a set of cameras that were installed on the floor or ceiling and secured with a rubber structure. There were also trackers to be monitored by the cameras. The "Extension" module allows connecting an external button to signal a shot (Gasanov et al., 2025).

As part of the study, we registered the coordinates of aiming points on the target, rifle position and rotation in standing position. Then the following graphs were generated: a correlation between rifle movement speed and time; a correlation between rifle rotation speed and time; a trajectory of aiming points coordinates registration on the target.

The data recorded from each subject include spatial rifle position, rifle movement and rotation speed, intersection point of the aiming line and the target in target coordinates. The sensors of the Antilatency optical tracking system also allowed posture tracking: five sensors were attached to the subject – two on the arms, two on the legs and one on the back. The sixth sensor was placed on the rifle, ensuring that it was displayed synchronously in virtual space and received the signal to shoot when the trigger was pulled.

Sample

The pilot study involved six subjects (2 male, 4 female, average age = 28, SD = 7), including three biathletes (two Masters of Sports and one Candidate Master of Sports); one Master of Sports in Aerobic; two subjects did not have sports qualifications. The inclusion criterion for athletes was to have a rank of at least a Master of Sports. The study was performed during the period from June through August 2024.

Data manipulation was performed using Python. The obtained data was visualized in graphs as follows: a) the correlation between the rifle movement speed and time, b) the correlation between the rifle rotation speed and time, c) the trajectory of aiming point coordinates on the targets. The graphs were purposed to determine the most prominent trends that would separate professionals from beginners.

Results

Figures 4.1-4.4 show the correlation between the rifle movement speed and time (Figures 4.1 and 4.3) and the correlation between the rifle rotation speed and time (Figures 4.2 and 4.4) for different subjects.

Figure 4.1

Correlation between the Rifle Movement Speed and Time, Master of Sports in Aerobic, 20 m

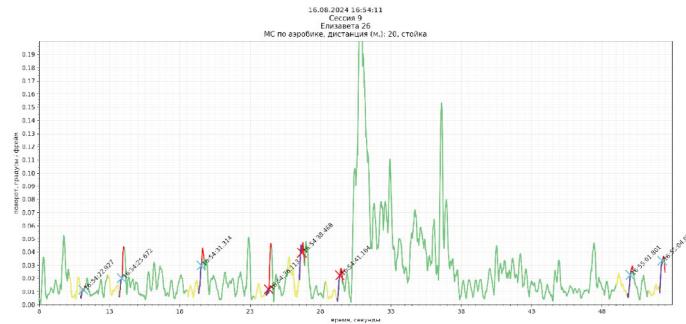


Figure 4.2

Correlation between the Rifle Rotation Speed and Time, Master of Sports in Aerobic, 20 m

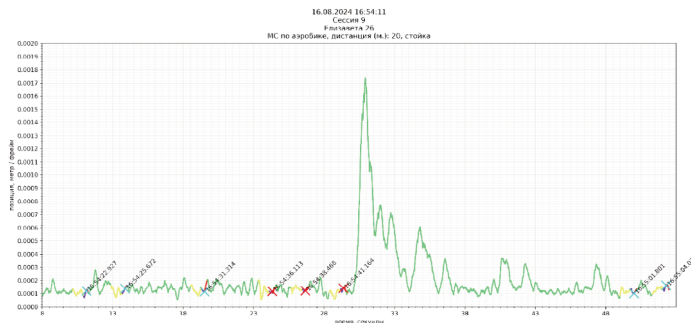


Figure 4.3

Correlation between the Rifle Movement Speed and Time, Candidate Master of Sports in Biathlon, 20 m

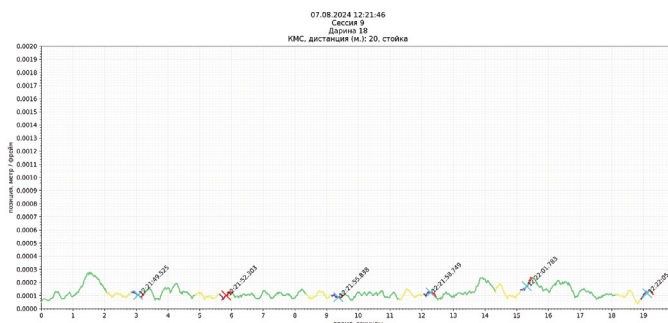
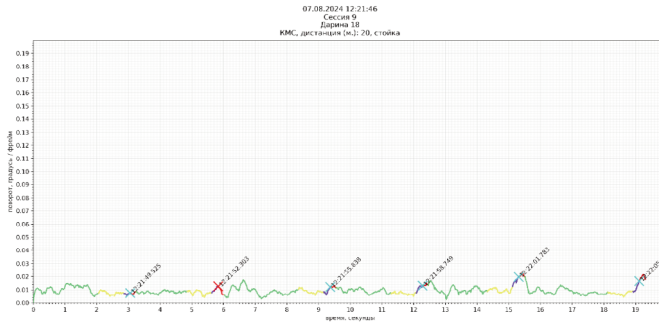


Figure 4.4

Correlation between the Rifle Rotation Speed and Time, Candidate Master of Sports in Biathlon, 20 m



Note. Interval of 1–0.2 s before the shot is marked yellow, the moment of the shot— 0.2 s before the shot is marked blue, 0.2 s after the shot is marked red, the rest of the time is marked green. Red crosses indicate misses, turquoise crosses — hits. Shot timing (a millisecond accuracy) is indicated next to the cross.

The graphs of rifle movement and rotation speed (Figures 4.1–4.4) show that the stability of aim holding increases right before a shot, whereby the rifle may suddenly jump when the trigger is pulled.

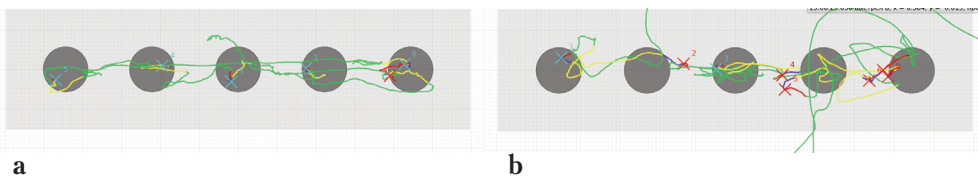
A similar shooting graph for a Candidate Master of Sports in biathlon shows that not only the overall speed of movement and rotation decreases (which speaks of a more stable target fixation), but also there are no jumps at the moment of shooting. The speed stability is considerably higher than that of a non-biathlete.

Figure 6 presents the trajectories of aiming point coordinates registration on the target. According to the graphs, one can see that a professional biathlete’s aiming point might have little or no horizontal target zone.

Non-professional biathletes tend to have the aiming point out of the target zone much more often. Keeping the aiming point is remarkably more challenging for

Figure 5

Coordinate Trajectory of Aiming Points on the Target: (a) Candidate Master of Sports in Biathlon, 20 m; (b) Subject without Sport Qualifications



Note. Interval of 1–0.2 s before the shot is marked yellow, the moment of the shot — 0.2 s before the shot is marked blue, 0.2 s after the shot is marked red, the rest of the time is marked green. Red crosses indicate misses, turquoise crosses — hits. Shot timing (a millisecond accuracy) is indicated next to the cross.

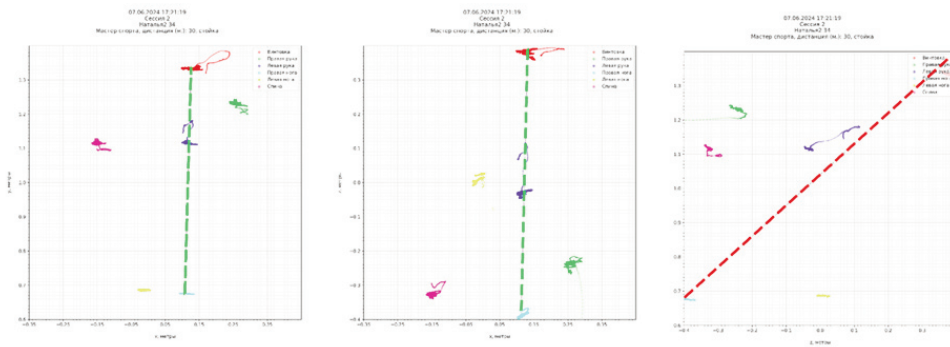
them. Also, the shots have different intervals, and there are visible pauses in the shooting.

The X and Y coordinates were also projected on the target image. The trajectory line was generated and divided into several intervals just as in Figures 4.1–4.4.

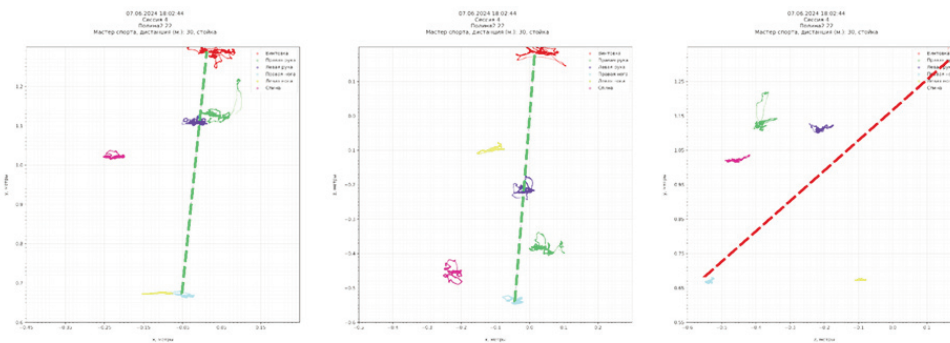
Based on the Antilatency tracker data, a scatter graph was generated for each tracker in a single coordinate plane. The study of biathletes' posture during shooting requires a considerable amount of follow-up research. Nevertheless, it seems of interest that a number of professional athletes' shootings reveal a clear “right foot – left hand – rifle” line in two of three planes. Graphs are shown in three planes – XY, XZ, and YZ, where X is directed to the athlete's right, Y is upward, and Z is forward (Figure 6 & 7).

Figure 6

Graph of Trackers Location in Different Coordinate Planes in Masters of Sports in Biathlon (Subjects N. and P.), Two Records Each



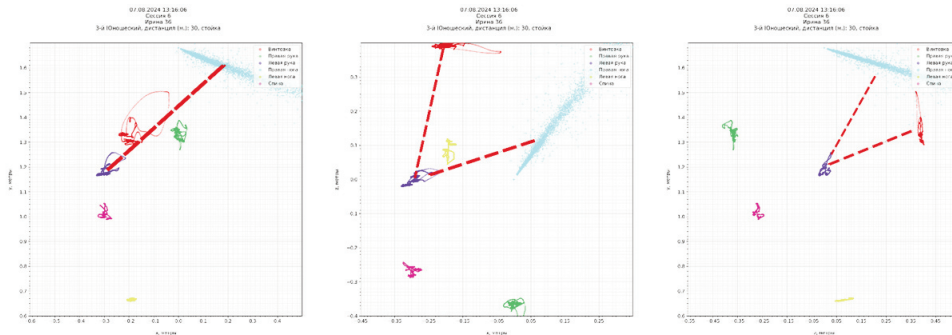
Subject N.



Subject P.

Figure 7

Graph of Trackers Location in Three Coordinate Planes in a Subject without Sport Qualifications



Discussion

Professional biathletes show a substantially greater aiming stability compared to non-biathletes. This was evident in a smoother trigger pull and a more uniform rifle movement and rotation speed. Their aiming trajectories show that they hold the aiming point within the target area, whereas non-biathletes' aiming point is more often out of target, which signals difficulty in holding the aim. Non-biathletes exhibit prominent pauses between shots, which indicates a deficiency in training. Meanwhile scatter graphs confirm the clear coordination between right leg, left arm and rifle movements in professional athletes, which appears to be a key factor in achieving high shooting accuracy.

These results are consistent with the literature, in particular with the studies that showed that biathletes, as well as general athletes, are better at static and postural balance compared to non-athletes (Sattlecker et al., 2014; Thompson et al., 2017; Sadowska et al., 2019a; Sadowska et al., 2020; Michalska et al., 2022).

Our study has confirmed the conclusions reported in a variety of studies regarding the importance of the body-rifle system stability in standing shooting among professionals (Era et al., 1996; Lakie, 2010; Niinimaa & McAvoy, 1983; Sattlecker et al., 2014).

The resulting scatter graphs for each of the Antiletancy system trackers showed that elite biathletes are distinguished by the stability of the body-rifle system in standing shooting, as manifested by a clear “right leg – left arm – rifle” line, which complements the existing data.

Thus, biathlon success depends on a combination of physiological, technical, and psychological factors that should be considered when training athletes to compete.

Conclusion

This pilot study using VR to validate it as a training tool for biathlon shooting has demonstrated the relevance of this tool and alignment with existing literature.

The obtained results on the graphs of correlation between the rifle movement speed and time, as well as correlation between the rifle rotation speed and time confirm the findings of previous studies on the significance of the body-rifle system stability for successful shooting in biathlon, where elite athletes demonstrate better postural balance, and less sway compared to beginners.

The analysis of scatter graphs of the Antiletancy system trackers highlighted a clear correlation between limb and rifle position, which emphasizes the relevance of fine postural control and reaction time.

Irrespective of the obtained results, the study of the posture and shooting technique of biathletes requires additional research to improve the understanding of shooting mechanics and optimize training.

In future studies, we plan to expand the sample size and focus on examining postural balance both under physical load conditions and in situations of psycho-emotional stress. Special attention will be given to the effects of distractors, such as noise, which simulate real competitive environments.

Limitations

This study has a number of limitations. The first is the modest sample size. This is due to the involvement of elite biathletes, the access to whom was limited. As this was a pilot study aimed at validating the designed VR technology for biathlon shooting, we believed it was appropriate to test it on subjects with different skill levels in biathlon, in another sport, as well as without any sports experience.

Expanding the sample as well as applying a variety of stress conditions are the target for the next phase.

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