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The Effect of Stroboscopic Training on Ankle Mechanics During Gait in Chronic Ankle Instability: Clinical Trials

Kronik Ayak Bileği İnstabilitesinde Yürüyüş Sırasında Stroboskopik Antrenmanın Ayak Bileği Mekaniğine Etkisi: Klinik Deneyler

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ABSTRACT Objective: To determine the effect of 6-week stroboscopic training on ankle gait mechanics in athletes with chronic ankle instability. **Material and Methods:** Thirty-nine participants were assigned to the stroboscopic group (SG, n=13), non-stroboscopic group (NSG, n=13), and control group (CG, n=13). Three-dimensional kinematic pretest gait analysis was performed with the Noraxon system. Ankle joint angles were recorded for 75 seconds while the athletes walked on a treadmill at a speed of 3.5 m/s. After the pretest, the SG performed 6 weeks of balance training with stroboscopic vision, the NSG performed 6 weeks of balance training without stroboscopic vision, and the CG received no training. Ankle gait analysis was repeated after 6 weeks. Repeated-measures analysis of variance with one between-subjects factor was performed. **Results:** Gait analysis revealed a significant increase in ankle dorsiflexion angle between pretest and posttest in the SG (p<0.001, ηp2=0.34). Between-group comparisons showed significantly higher dorsiflexion angle in the SG compared to the CG (p=0.001, ηp2=0.15) and NSG (p=0.002, ηp2=0.11). Gait analysis of 100 kinematic data points starting at heel strike was performed using MATLAB. The results demonstrated the increase in ankle range of motion in the SG occurred in the dorsiflexion angle during the midstance phase of gait. **Conclusion:** Stroboscopic glasses modulate visual feedback and may be clinically useful in allowing progressive rehabilitation targeting the dependence on visual feedback for motor control.

Keywords: Ankle injuries; gait analysis; vision perception

ÖZET Amaç: Kronik ayak bileği instabilitesi olan sporcularda 6 haftalık stroboskopik eğitimin ayak bileği yürüyüş mekaniklerine etkisinin belirlenmesidir. **Gereç ve Yöntemler:** Otuz dokuz sporcu gözlüklü grup (n=13), gözlüksüz grup (n=13), kontrol grup (n=13) olmak üzere 3 gruba ayrıldı. Sporculara Noraxon cihazı ile 3 boyutlu kinematik ilk test yürüyüş analizi yapıldı. Bilgisayar programına entegre olan sensörler yardımıyla koşu bandı üzerinde 3,5 m/sn hızla 75 sn yürüyen sporcuların ayak bileği eklem açı kayıtları alındı. Ilk testten sonra gözlüklü grup 6 haftalık stroboskopik denge eğitimi, gözlüksüz grup 6 haftalık denge eğitimi yaptı. Kontrol grubu eğitim yapmadı. Altı hafta sonra ayak bileği yürüyüş analizi tekrarlandı. Tekrarlı ölçümlerde varyans analizi bağlı olmayan gözlemler arası faktör analizi kullanıldı. **Bulgular:** Yürüyüş analizi ölçüm sonuçlarında ayak bileği dorsifleksiyon açısında ilk test son test sonuçlarında, gözlüklü grup lehine anlamlı fark bulundu (p<0,001, ηp2=0,34). Gruplar arasında yapılan karşılaştırmada gözlüklü grubun sonuçlarında, kontrol grubu (p=0,001, ηp2=0,15) ve gözlüksüz gruba (p=0,002, ηp2=0,11) göre artış yönünde anlamlı fark bulundu. Ardından tespit edilen topuk vuruşu ile başlatılan 100 kinematik veri noktası MATLAB programı ile yürüyüş analizi süreci işlendi. Yürüyüş analizi sürecinde tespit edilen gözlüklü gruptaki dorsifleksiyon açısındaki artışın orta duruş fazı boyunca meydana geldiği tespit edildi. **Sonuç:** Görsel geri bildirimi modüle edebilen stroboskopik gözlükler, görsel geri bildirim bağlı motor kontrolü artırmayı hedefleyen ilerleyici rehabilitasyona izin verilmesinde klinik olarak yararlı olabilir.

Anahtar Kelimeler: Ayak bileği yaralanmaları; yürüyüş analizi; görme algısı

Chronic ankle instability (CAI) is characterized by repetitive episodes or perceptions of the ankle giving way; ongoing symptoms such as pain, weakness, or reduced ankle range of motion (ROM); diminished self-reported function; and recurrent ankle sprains for more than a year after the initial injury.[1] Gait modifications may result from mechanical and neurological abnormalities in the joint following an ankle sprain.[2,3] The ankle is the foundation of the kinetic chain, thus any functional impairment there can lead

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to problems in the more proximal joints. Unfavorable gait modifications put the proximal joints at risk for compensatory injuries given the repetitive nature of the loads during locomotion.[4] A systematic review showed that individuals with CAI had increased frontal displacement and limited sagittal displacement.[5] It has also been determined that plantar flexion is increased during heel strike, and dorsiflexion is reduced during midstance (9%-25% of gait cycle).[6] Reduced dorsiflexion ROM may also cause a feeling of instability. By constraining the bony articulation of the joint during movement, limited sagittal ROM may reduce joint stability. According to one study, performing one-legged poses with the eyes open and closed as part of a static postural stability exercise reduced the forces acting on the ankle, the ground response force experienced while walking, and the angle of plantar flexion upon contact.[7]

One of the main problems related to CAI is identifying patients in need of treatment. People often perceive ankle injuries as minor, and return to their normal activities after the initial pain and swelling subsides. Furthermore, most treatments focus on ankle sprains as a local injury. In fact, ankle sprains are a broader neuromechanism injury that not only affects local tissues, but involves the overall neuromuscular system and even how the brain controls the muscles to create movement.

The central nervous system needs enough afferent input from vision and somatosensation to control motor function and preserve neuromuscular integrity during action and environmental interaction.[8-10] A meta-analysis suggested that individuals with CAI prioritize visual information during motor feedback activities, likely due to inaccurate somatosensory input.[11] Sport maneuvers that disrupt visual input can directly access compensatory neuroplastic sequelae following injury and functionally re-train the neuromuscular system. A technological innovation called stroboscopic vision, which is characterized by intermittent visual obstruction, can be used as a tool to enable clinicians to progressively examine the effects of sensory feedback with incomplete visual information. By modulating visual feedback, stroboscopic glasses may be clinically useful both to determine how patients with somatosensory deficits rely on visual feedback for postural control, and to facilitate progressive rehabilitation aiming to increase motor control dependent on visual feedback.[12] It has also been reported to increase visual motor control and have utility in the prevention of anterior cruciate ligament injuries.[13,14] In terms of athletics, it was determined that stroboscopic training led to improved on-ice skills in professional ice hockey players and enhanced performance and reaction speed in baseball and badminton.[15-17] Also, a recent study showed that stroboscopic training was effective in reducing visual reliance and increasing motor control during single-limb balance, as well as improving postural control in athletes with CAI.[18] Therefore, we predict that the neuromuscular process by which stroboscopic training improves ability and performance in sports may also apply in CAI.[15-17]

The purpose of this study was to examine how stroboscopic balance training affects ankle mechanics during gait in athletes with CAI. Our hypothesis was that stroboscopic training would improve ankle mechanics during gait.

MATERIAL AND METHODS

Of 126 athletes evaluated for inclusion in this study examining the effects of stroboscopic balance training on gait mechanics in athletes with CAI, those who met the International Ankle Consortium criteria for CIA were selected: A history of a moderate to severe unilateral ankle sprain (>8 days of lost sports time) accompanied by inflammatory symptoms, swelling, and pain within the previous 5 years but at least 1 year before enrollment; a score at least 11 on the Identification of Functional Ankle Instability Questionnaire; at least 2 episodes of ankle giving way in the 6 months prior to enrollment; a score of less than 90% on the Foot and Ankle Ability Measure Activities of Daily Living scale; and a score of less than 80% on the Foot and Ankle Ability Measurement-Sport scale.[19-21] The study only included athletes with unilateral CAI.[22] Power analysis was performed using the G-Power (latest ver. 3.1.9.3; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) program. In order to assess post-training variations in three-dimensional (3D) gait mechanics with 0.79 effect size, 5% Type 1 error, and 80% power, 13 participants were recruited for each of the three groups.[23]

Using statistically generated opaque sealed envelopes, the athlete participants were randomly assigned using an allocation ratio of 1:1:1 into the stroboscopic group (SG, n=13), non-stroboscopic group (NSG, n=13), and control group (CG, n=13). Participants in the SG and NSG underwent 3D ankle analysis during gait before the training and after 6 weeks of training; participants in the CG underwent the same analysis twice at an interval of 6 weeks. Senaptec brand (Beaverton, Oregon) stroboscopic glasses were used in the SG. Figure 1 shows the study flowchart. The study was conducted in accordance with the principles of the Declaration of Helsinki. All participants provided their informed consent, and ethical approval was obtained from the Nevşehir Hacı Bektaş Veli University Ethics Committee (date: November 16, 2018, no: 2018.14.163).

BALANCE TRAINING PROGRAM

Every participant in the NSG and SG took a part in a balance training program three days a week for a total 6 weeks.[22] The CG did not receive balance training. The athletes in the NSG performed the balance exercises normally, while the athletes in the SG used strobing glasses (Senaptec, Beaverton, Oregon) with a switching frequency of 100 ms clear/150 ms dark (Figure 2). We considered level 3 (100/150 ms) to be a safe setting for the participants given the higher risk of injury with longer opacity phases.

The balance training program included exercises previously described and shown to be effective in enhancing balance in CAI.[22] Each session started with a 5-minute warm-up consisting of jogging and gentle Achilles tendon stretching (progressing from 3 to 7 repetitions). Sessions lasted a total of 15 to 20 minutes on average. The program included the following exercises:

1. Single-leg Hop to Stabilization (on the injured leg): Participants performed 10 hops in each of 4 directions (posterior/anterior, lateral/medial, posterolateral/anteromedial, and posterolateral/ anterolateral).[22]

2. Hop to Stabilization and Reach: Participants hopped, stabilized, and reached back to the starting

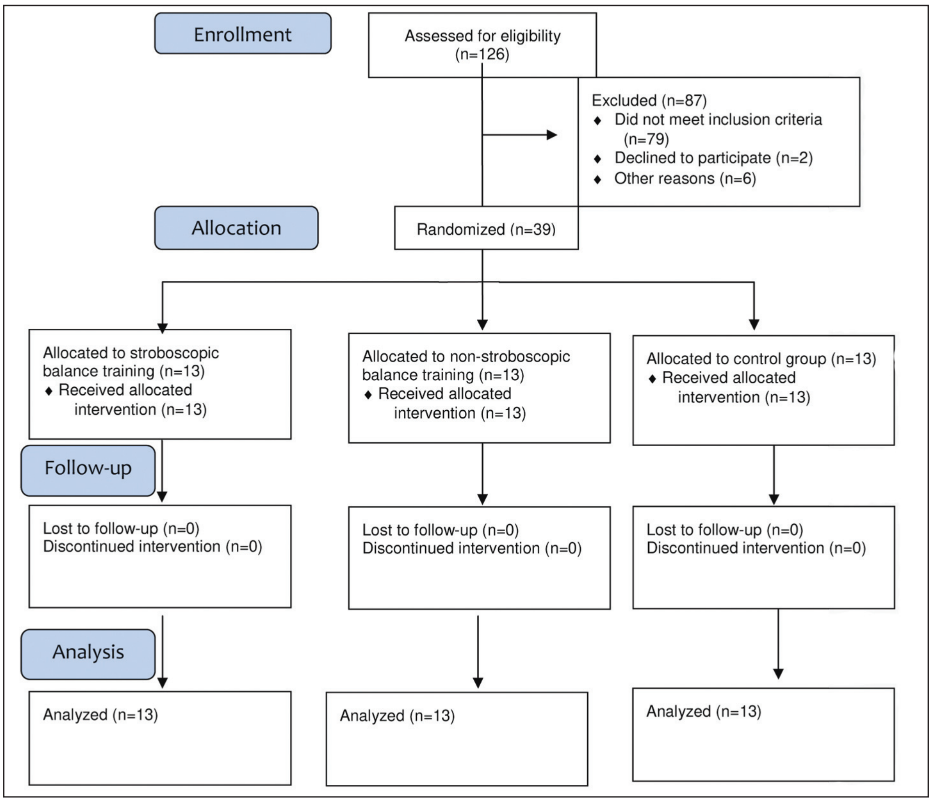

FIGURE 1: Participant flow diagram.

FIGURE 2: Strobe glasses.

position. Then they hopped back to the starting position and reached to the target position (5 repetitions).[22]

3. Unanticipated Hop to Stabilization: Markers numbered 1 to 9 were placed on the floor in a 3x3 grid. The participants had to maintain their balance while hopping on their injured leg toward the target numbers, starting in the center of the grid and utilizing any combination of hops they desired. Computer algorithms were used to generate three random target number sequences (1-9).[22]

4. Single-Leg Balance: Participants performed three repetitions of single-limb stance activities with open and closed eyes, using varying foam pads every week.[22]

Each participant did the same exercises every week, and the difficulty level was increased each week. All the participants performed the same exercises with the same level of difficulty. Participants could only progress to a higher difficulty level after demonstrating proficient movement (i.e., without error) for each iteration of a particular direction or activity, or both. Exercise-specific progressions in training difficulty included adding unstable surfaces, lengthening the duration of the balance activities, increasing hop length, placing hands on hips while hopping, or any combination of these. Throughout the program, progression was assessed independently by a physiotherapist with approximately 15 years of experience.

THREE-DIMENSIONAL GAIT ANALYSIS

The inertial measurement unit (IMU)-based system MyoMotion (Noraxon U.S.A. Inc., Scottsdale, USA) was used for motion analysis focused on the objective and dynamic detection of joint angles. A total of 7 IMU sensors were attached to the participants using straps or clips according to the manufacturer's specifications (Figure 3). The participants were asked to stand upright and still while a physiotherapist placed the sensors. To ensure that the sensors were in the same position for both assessments, sensors on the leg and thigh were placed using distance measurements from the lateral malleolus and tibial tuberosity, respectively, and circumference measurements. The sensors were placed at the following standardized locations: one centrally on the posterior pelvis over the S1 vertebra, with the x-axis pointing upwards; a total of 4 on the anterior thighs and calves, and 1 on the dorsum of each foot. The leg sensors were each positioned centrally from the frontal view on the thigh and shin below the main muscle belly, with the x-axis pointing upwards parallel to the leg axis. The MyoMotion system allows measurements with a sampling frequency of 100 Hz and accuracy to 1°.[24]

FIGURE 3: Sensors for 3D gait-analysis.

After placement, the sensors were calibrated and each participant performed 3 trial walks. Using these sensors and the integrated computer program, recordings were obtained as the athletes while walking on a treadmill at 3.5 m/s for 75 seconds (Figure 4).

The angle of the participants' ankles was recorded in degrees throughout the gait cycle. Images were also recorded by the program using a synchronized camera (Figure 5).

STATISTICAL ANALYSIS

IBM SPSS Statistics version 22.0 was used to analyze the data (IBM Corp, Armonk, NY). Using the Shapiro-Wilk test, the normality of the data distributions was evaluated. The repeated-measures analysis of variance with one fixed factor was performed. Bonferroni correction was used in multiple comparisons. Data were summarized as mean±standard deviation. Partial eta squared (η_p^2) was used to measure effect size. Effect sizes of $^{3}0.14$ were interpreted as large, 0.01-0.06 as medium, and <0.01 as small.[25] A p value of <0.05 was regarded as statistically significant.

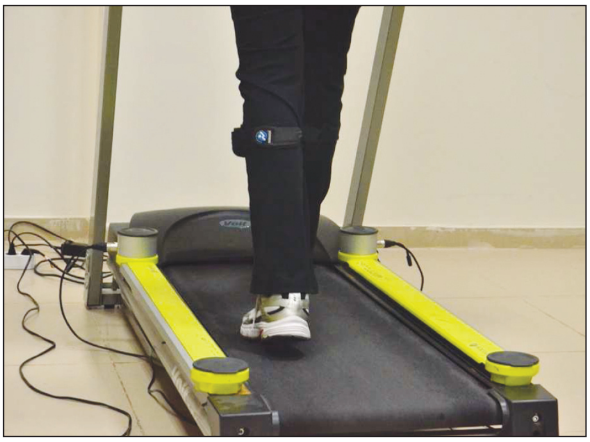

FIGURE 4: 3D gait analysis on the treadmill.

RESULTS

PARTICIPANTS

The study sample consisted of 39 participants in total, including 19 women (height: 1.63±0.07 m, age: 19.74±1.52 years, weight: 57.6±9.57 kg) and 20 men (height: 1.76±0.05 m, age: 20.10±1.80 years, weight: 69.3±7.16 kg). Of these, 13 underwent training using stroboscopic glasses (SG; mean age: 19.08±0.40 years), 13 received the training without stroboscopic glasses (NSG; mean age: 20.46±0.51 years), and 13 received no training (CG; mean age: 20.23±0.39 years). The groups were homogeneous in terms of gender distribution, age, height, weight, and other initial parameters (Table 1).

RESULTS OF 3D GAIT ANALYSIS

Ankle dorsiflexion angle in the SG significantly increased in the posttest compared to the pretest ($p<0.001$, $\eta_p^2=0.34$) (Table 2). In the between-group comparison, posttest dorsiflexion was significantly greater in the SG than the CG ($p=0.001$, $\eta_p^2=0.15$) and NSG ($p=0.002$, $\eta_p^2=0.11$).

FIGURE 5: Gait analysis records.

The results indicated statistical differences in mean ankle dorsiflexion ROM values. Considering that walking is a cycle, it is important at what point this difference occurs. The gait analysis values were processed into 100 points by the Noraxon system's dedicated software to determine where this statistical difference originated. These 100 kinematic data points starting with the detection of the heel strike were processed with MATLAB (version R2015b; The mathWorks Inc, Natick, MA) to complete the gait analysis process. The ankle flexion angles in the study groups throughout the gait cycle before and after training are shown in Figure 6 and Figure 7, respectively (SG shown in blue, NSG in red, CG in green). The outcomes

TABLE 1: Demographic characteristics.

	Control group (n=13)	Stroboscopic training (n=13)	Non-stroboscopic training (n=13)	p value
Gender (n M/F)	6/7	7/6	7/6	
	X̄±SD	X̄±SD	X̄±SD	
Age (years)	20.23±0.39	19.08±0.40	20.46±0.51	0.071
Height (m)	1.72±0.02	1.70±0.02	1.68±0.02	0.630
Weight (kg)	66.06±2.40	63.19±3.39	61.69±2.69	0.553
IDFAI score	19.46±1.58	16.54±1.32	17.54±1.32	0.343
FAAM				
ADL Subscale	79.92±2.82	84.07±1.32	80.73±2.00	0.358
Sports Subscale	59.84±4.71	67.03±5.33	65.05±4.33	0.557

n: Number of participants; p<0.05: statistical significance; SD: Standard deviation; IDFAI: Identification of Functional Ankle Instability Questionnaire; FAAM: Foot and Ankle Ability Measure; ADL: Activities of daily living.

TABLE 2: Results of ankle 3D gait analysis.

	X̄±SD								
	Control group (n=13)			Stroboscopic group (n=13)			Non-stroboscopic group (n=13)		
3D analysis results	Baseline	Posttest	ηp²	Baseline	Posttest	ηp²	Baseline	Posttest	ηp²
Dorsiflexion	36.8±1.59	35.54±1.34†	0.02	36.8±1.59	42.9±1.34†,*	0.34	35.3±1.59	35.9±1.34†	0.04
Inversion	27.2±1.45	25.7±1.70	0.02	23.8±1.45	24.41±1.70	0.03	28.24±1.45	26.50±1.70	0.03
Eversion	23.78±1.62	22.96±1.52	0.01	24.11±1.62	24.33±1.52	0.01	24.01±1.62	23.90±1.52	0.01

*Significant pretest–posttest change (p<0.05); †Significant between-group difference (p<0.05); Mixed repeated-measures analysis of variance; n: Number of participants; ηp2: Partial eta squared; SD: Standard deviation

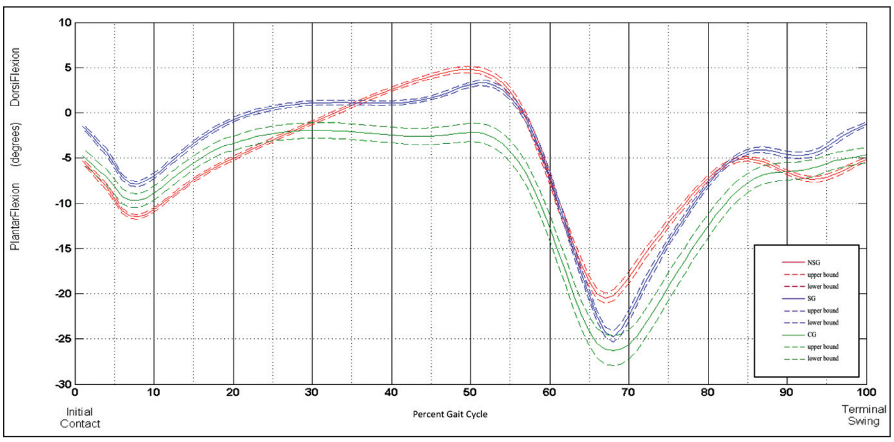

FIGURE 6: Gait analysis before balance training.
NSG: Non-stroboscopic group; SG: Stroboscopic group; CG: Control group.

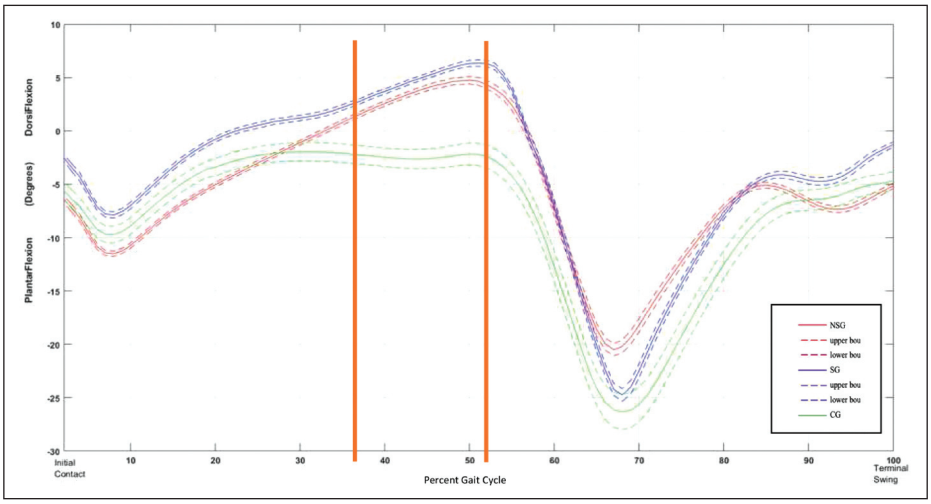

FIGURE 7: Gait analysis after balance training.
NSG: Non-stroboscopic group; SG: Stroboscopic group; CG: Control group.

demonstrated that the statistical difference was a result of increased dorsiflexion angle during midstance (38-52% of the gait cycle) (Figure 7).

DISCUSSION

The objective of this study was to demonstrate how stroboscopic balancing training modified ankle mechanics during gait in CAI. The results of the study showed that stroboscopic balance training can lead to motor changes that are enhanced by stroboscopic vision. On gait analysis we observed an increase in ROM (42.9±1.34) in the athletes who received stroboscopic balance training. Several studies have indicated an overall ROM in the sagittal plane of between 65° and 75°, moving from 10-20° of dorsiflexion through to 40-55° of plantar flexion.[26] However, in everyday activities, the ROM required in the sagittal plane is much lower, with a maximum of 30° for walking.[27] In a study conducted on individuals with and without CAI, it was observed that healthy individuals could make plantar flexion angles of 15° and dorsiflexion angles of 20° in the sagittal plane.[28]

We determined that the observed increase in ROM occurred in the dorsiflexion angle, especially during the midstance phase. A previous study suggested that dorsiflexion in patients with CAI was reduced between 9% and 25% of the gait cycle, which corresponded to midstance.[6] Another study indicated that while walking, the CAI group had an average of almost 3° less dorsiflexion between 42% and 51% of the gait cycle compared to the CG.[28] In our study, it was determined that the dorsiflexion angle increased between 38% and 52% of the gait cycle. The increase in midstance dorsiflexion observed in athletes with CAI after stroboscopic balance training suggests the effectiveness of this intervention. Although both the SG and NSGs received the same 6-week exercise intervention, it is noteworthy that the improvement in dorsiflexion was observed only in the group who performed the exercises while wearing the stroboscopic glasses. It has been suggested that visual disruption during movement tasks requires the central nervous system to reorganize motor output by increasing the weighting of somatosensory and vestibular inputs.[8] Stroboscopic glasses alter visual feedback and thus may be clinically effective in increasing motor control dependent on visual feedback.[12] Studies have shown that compared to uninjured controls, individuals with CAI have a reduced capability to effectively compensate for center-of-pressure changes that occur when somatosensory inputs from around the foot/ankle complex are eliminated (by anesthetic injection into the ankle) or replaced (with textured insoles placed in footwear).[29,30] However, this improvement might signify superior motor planning and execution in athletes with CAI.[31,32] Another study demonstrated that training can lead to changes in the motor area (Cz alpha and theta waves) and that these changes are enhanced by stroboscopic vision.[18] The increase in cortical activity in response to changing the visual input could be interpreted as consistent with increasing somatosensory control, which may alter the neuromuscular control mechanism. Visual stimuli elicit cortical responses in the occipital regions and improve the brain's ability to adapt to changes in sensory input.[33] An athlete intermittently seeing their surroundings may increase their motor performance by directing both their focus and concentration completely to the exercise. This is the rationale for performing training exercises with eyes open and eyes closed in traditional rehabilitation interventions.

Studies on elite athletes in several sports have revealed that stroboscopic training enhances performance in badminton, ice hockey, and baseball.[15-17] In several low-level perceptual domains, such as transient attention selectivity and foveal motion sensitivity, stroboscopic training has been shown to increase visual sensitivity and improve visual motor reaction time.[34,35] This association between motor movement and visual sensitivity is noteworthy. The stroboscopic effect is believed to force the visual system to more effectively perceive and interpret visual data. In this case, it can be concluded that the increase in ankle dorsiflexion angle in this study is related to visual-motor activity.

For patients with CAI, it is clinically significant that the limited dorsiflexion angle in midstance increases as a result of stroboscopic training. This training can be applied during balance training without additional effort on the part of the physiotherapist, like other perturbations used in balance training. Our findings further highlight the importance of balance training in athletes and suggest that intermittent vision can be simply added to conventional balance training for athletes as an extra technique that increases the challenge of maintaining balance. Stroboscopic glasses are a practical device for use in conventional training because they are portable, convenient, and easily accessible. Additionally, stroboscopic training can easily be integrated into the training programs of athletes who must perform balance exercises because of lower limb injuries, chronic illnesses linked to balance problems, or sports requiring advanced balance, such as gymnastics, archery, skiing and snowboarding. Future clinical research is required to compare the outcomes of stroboscopic balance training to more conventional rehabilitation methods. Various objective assessment techniques can be used to conduct a more thorough evaluation.

CONCLUSION

This study examined how 6 weeks of stroboscopic balance training affected the mechanics of gait in athletes with CAI. We believe balance training programs utilizing stroboscopic glasses may be clinically beneficial not only for athletes with somatosensory problems by reducing visual dependence in athletes with CAI, but also by restricting visualization and increasing motor control movement, especially in progressive exercise parameters during the return-to-play phase of rehabilitation. Given the perturbation effect of stroboscopic glasses, they can be easily used by sports physiotherapists as a balance training tool both during the rehabilitation of injured athletes and in training programs.

Source of Finance

During this study, no financial or spiritual support was received neither from any pharmaceutical company that has a direct connection with the research subject, nor from a company that provides or produces medical instruments and materials which may negatively affect the evaluation process of this study.

Conflict of Interest

No conflicts of interest between the authors and / or family members of the scientific and medical committee members or members of the potential conflicts of interest, counseling, expertise, working conditions, share holding and similar situations in any firm.

Authorship Contributions

Idea/Concept: *Serkan Uzlaşır, Volga Bayrakçı Tunay;* ***Design:*** *Serkan Uzlaşır, Volga Bayrakçı Tunay;* ***Control/Supervision:*** *Serkan Uzlaşır;* ***Data Collection and/or Processing:*** *Serkan Uzlaşır;* ***Analysis and/or Interpretation:*** *Serkan Uzlaşır, Osman Dağ;* ***Literature Review:*** *Serkan Uzlaşır;* ***Writing the Article:*** *Serkan Uzlaşır;* ***Critical Review:*** *Volga Bayrakçı Tunay;* ***References and Fundings:*** *Serkan Uzlaşır;* ***Materials:*** *Serkan Uzlaşır.*

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