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**Original Article**

# Enhancing vertical jump performance through real-time biofeedback: A randomized controlled trial in healthy individuals

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**Abstract**:
Real-time biofeedback (Rt-Bf) has gained substantial recognition in recent years as an invaluable tool in the fields of rehabilitation and sports medicine. Its application has piqued the interest of professionals across a wide spectrum of sports settings, making it a pivotal focus of research. The primary objective of this study was to investigate how the integration of biofeedback into training programs could impact the vertical jump and balance outcomes in healthy subjects, in direct comparison to traditional approaches such as verbal instructions (VER) and video observation (VO). A total of 262 active healthy subjects were randomized into three groups: VER, VER + VO, and VER + Rt-Bf. The subjects underwent a vertical jump test (squat jump) and a balance test (single-leg squat) following a pre-established protocol. After a 5-min rest period, the tests were repeated. During the rest period, each group received specific interventions: VER group received verbal instructions, VO group watched a video execution, and Rt-Bf group received real-time biofeedback. Gyko® technology was employed as the measuring tool, capturing and analyzing all relevant parameters associated with both the jump and balance protocols. The Rt-Bf group exhibited a significantly higher improvement in jump height (2.3 cm) compared to the other groups ($p < 0.001$). While the Rt-Bf group also demonstrated enhancements in various parameters of the single-leg squat, these improvements were not statistically significant ($p > 0.05$). The findings suggest that incorporating an Rt-Bf protocol alongside VER significantly enhances vertical jump performance. Although balance parameter improvements were also observed in the Rt-Bf group, they did not reach statistical significance ($p > 0.05$). These findings reaffirm the pivotal role that Rt-Bf plays in augmenting physical performance in healthy individuals, offering a promising avenue for future research and application.
**Key Words**:-**motor learning; neuromuscular training; rehabilitation; movement pattern restoration; real-time biofeedback**

## Introduction

Strategies for learning motor tasks are crucial in rehabilitation and sports medicine, as they play a role in preventing injuries and enhancing performance [Larsen et al., 2016]. Among these strategies, biofeedback is gaining particular interest in the current scientific literature. Biofeedback is a non-invasive, non-pharmacological, self-regulation technique through which patients learn to control what was once thought to be involuntary body processes. It provides biological information in real-time that would otherwise be unknown [Frank et al., 2010; Giggins et al., 2013]. Biofeedback training requires specialized equipment to measure biomedical variables and communicate them to the patient, directly or indirectly. The relevant variables are transformed into a visual, acoustic, or other feedback signal that is easy to interpret [Giggins et al., 2013]. By providing real-time data to the patient, biofeedback empowers them to understand and modify their physiological functions. It is used in various settings to improve academic, athletic, and corporate performance as well as health and wellness [Frank et al., 2010].

Even if some applications to the vibrotactile or audio fields already exist, biofeedback methods have recently become very popular in sports medicine settings [Blumenstein & Orbach, 2014]. In addition, it has been shown that biofeedback interventions can facilitate the transfer of training in different skills, specifically in motor learning and in perfecting movement techniques [Issurin, 2013]. Biofeedback has also gained importance


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in sports injury prevention and rehabilitation to restore movement patterns after injury [Tate & Milner, 2010]. Because the risk of musculoskeletal injury, specifically anterior cruciate ligament (ACL) injury, is associated with decreased neuromuscular control and coordination during dynamic activities, neuromuscular training (NMT), often with the use of biofeedback tools, has been introduced as a well-established training intervention to affect modifiable biomechanical risk factors, aiming to potentially reduce the risk of injury in athletes [Hewett et al., 2005; Sugimoto et al., 2015].

For instance, Molka et al. [2015] stated that visual feedback exercises have been used as a one-month training program after ACL reconstruction, leading to improvement in proprioception and enhancing the ability to perform static and dynamic balance tasks. Although NMT effectively reduces the risk of injury, conventional approaches primarily target biomechanical factors, such as muscle strength, balance, and plyometric function, with less consideration of cognitive components [Grindstaff et al., 2006; Yoo et al., 2010; Myer et al., 2008; Myer et al., 2012]. Given this limitation, NMT could be implemented by selecting key biomechanical, physiological, or neuromotor variables of training. For example, balance and jump performance are critical aspects of athletic performance, influencing both the effectiveness of movement and injury risk [Romano et al., 2021]. The implementation of real-time biofeedback (Rt-Bf) in these tasks could increasingly improve neuromuscular function and potentially decrease the risk of re-injury by examining sensory and neural variables that contribute to post-injury disability [McLean, 2008; Gokeler et al., 2013]. For example, Bonnette et al. [2020] demonstrated the feasibility and preliminary effectiveness of an interactive Rt-Bf system, showing positive changes in participants' biomechanics from the pre-to post-test period.

They concluded that the Rt-Bf used in their study effectively reduced ACL injury in an athlete population defined/evaluated as a high risk of re-injury. To the best of our knowledge, the integration of biofeedback-based exercises into training programs, either in conjunction with or compared to verbal instructions (VER) and video observation (VO), has seldom been considered in the healthy general population that does not need to rehabilitate from an injury [Blumenstein & Orbach, 2014]. This could be an interesting aspect to consider because a healthy subject could have different needs from an injured athlete, and biofeedback itself could have a potential role in that sense. Therefore, the aim of this study was to evaluate the effectiveness and change in performance following VER plus Rt-Bf or VO-based training on vertical jump and balance outcomes in healthy subjects.

## Material & methods

*Experimental Approach to the Problem*

This trial was designed as a single-blinded, randomized, three-arm parallel-controlled trial. This study was designed according to the Consolidated Statement of Reporting Trials 2010 (CONSORT) [Schulz, Altman, & Moher, 2010] and the Template for Intervention Description and Replication guidelines (TIDieR) [Hoffmann et al., 2014]. We chose to randomize the subjects with block randomization, with a 1:1:1 allocation using an online service (https://www.sealedenvelope.com/simple-randomiser/v1/lists)

*Subjects*

Before the visit, each patient signed informed consent to accept medical procedures and data collection. All information was recorded anonymously. Moreover, the data collection form specifies that data should be used for scientific purposes in aggregate form while maintaining the privacy of each subject. Data have been treated according to privacy rules and protection. All procedures performed in this study were in accordance with the Helsinki Declaration and its later amendments or comparable ethical standards.

*Study Setting*

The setting of this study was the annual "Ferrari Formula Benessere" program, a corporate wellness program that includes several medical activities and is firmly focused on the concept of primary prevention and exercise prescription in the general population [Biffi et al., 2022; Sirico et al., 2020; Palermi et al., 2022]. Recruitment occurred between October and December 2022.

*Eligibility Criteria*

Participants were recruited on a voluntary basis among healthy adults (age > 18 years) at the corporate wellness program. Participants were included if they were able to understand instructions in Italian and perform a jump and land task safely. No sports disciplines or sports activity restrictions were applied. Therefore, a convenient consecutive sample of subjects was selected for the scope of the study. Participants were excluded if they had any history of musculoskeletal, neurological, or orthopedic disorders in the lower extremities within the preceding six months or if they had a loss of vision that prevented them from seeing the video feedback.

*Procedures*

*- Randomization and Blinding*

Blocked randomization with a 1:1:1 allocation in three groups was performed for this study; using a random block size of 6 per group, participants' identity was ensured by an opaque envelope. The participants were divided into three groups: no intervention group (Ctrl), video observation group (VO), and real-time biofeedback group (Rt-Bf). Allocation concealment was ensured by keeping the randomization list under the care of one person with no involvement in the measurements (DZ). The allocation sequence was concealed until the patients were enrolled and assigned to interventions. The investigators that analyzed the data (SP, FS, AB) were blinded to the allocated treatment during the entire period of data collection. This was preserved by masking the groups and subjects and by assigning an alphanumeric code. During the study, subjects were asked to refrain from discussions around the protocols, to avoid observing others during the execution of the protocol, and to abstain from sharing any information about the study.

*- Intervention*

All subjects received a one-to-one interview comprising five minutes of verbal explanation (VER) of the protocol by a specialized trainer (LB) before the initial jump and balance tests (t0). The verbal explanation consisted of a detailed illustration of the exercises in the balance and jump protocol. Then, three different strategies were applied to the three groups before repeating jump and balance tests (t1).

The Ctrl group received only a refresh of the VER and repeated the balance and jump protocol. A video representing an athlete performing the correct jump and balance protocol was shown to the VO group. The video watched on a laptop 15" screen at a distance of 3 m, had both audio and video explanations.

Subsequently, the subjects repeated the jump and balance protocol. The Rt-Bf group repeated the balance and jump protocol whilst watching real-time biofeedback performed using specific software. In the jump protocol, the software showed a bar graph representation of the jump height. In the balance protocol, the patient was able to observe on a screen a graphical representation through a red-dot center of pressure displacement and was invited to hold it still.

*Measures*

Before testing, all participants underwent a standardized five-minute warm-up, which included submaximal polymetric and skipping exercises. All measurements were taken on the same day for all groups, in the morning, in a room with a standardized temperature of 21° C. Subjects were asked to avoid physical exercise 24 hours before the measurement. A rest period of 5 min was observed between the jump and balance protocols. All parameters in both jump and balance protocols were measured using Gyko ® (Microgate, Bolzano – Italy), an accelerometer tool that provides information on several kinematic parameters [Spera et al., 2019]. This tool is reliable in both jump [Lesinski, Muehlbauer, & Granacher, 2016] and balance [Jaworski et al., 2020] assessments.

*Jump Protocol*

The jump protocol consisted of a squat jump test [Spera et al., 2019]. Subjects were required to remain in a static position with a 90° knee flexion angle for 2 s before jumping, without any preparatory movement, and with their hands fixed along their hips [Loturco et al., 2017]. After an initial command, they jumped as high as possible. This routine was performed three times without rest between repetitions, and the best score was used for analysis. Jump height (SJ) was assessed using Gyko software.

*Balance Protocol*

The balance protocol consisted of a single-leg stance test [Spera et al., 2019], which is a widely used test with normative data accepted by the scientific community [Springer et al., 2007]. The subjects had to choose their dominant foot. They were asked to complete the task with their eyes open, barefoot, with their arms along the sides of their body, and to bend the contralateral knee so that it did not have any contact with the weight-bearing knee.

They had to stand on their dominant foot as long as they could: when the subject touched the floor with the non-dominant foot, the test was stopped. Three attempts were made, and the best trial score was used for analysis [Springer et al., 2007]. Parameters studied for this task were the ellipse area (EA), length (L), mean distance (MD), and velocity (V) [Russo et al., 2015; Russo et al., 2020; Penna et al., 2023].

*Statistical Analysis*

Data analysis was performed using the STATA software® (StataCorp. v.12, College Station, TX, USA). The primary outcome of the study was to assess the change in jump and balance outcomes following Rt-Bf training compared with the VO or Ctrl groups. Therefore, the null hypothesis of the study was that the specific Rt-Bf would have no impact on jump and balance outcomes.

The normal distribution was assessed using the Shapiro-Wilk test. Quantitative variables are summarized as mean (m) and standard deviation (SD), whereas categorical variables are presented as absolute values (n) and percentages (%). If the data were not normally distributed, median and interquartile ranges were used. Changes from pre- to post-intervention were tested using paired t-tests. Changes in all groups between t0 and t1 were assessed. Significant differences among groups were analyzed using ANOVA. A p-value $< 0.05$ was considered statistically significant.

**Results**

In total, 262 subjects were considered eligible for this study, including 228 males and 34 females, with an average age of 39.46 (± 8.25) years. Subjects were randomly assigned to the Ctrl (n=88), VO (n=86), and Rt-Bf (n=88) groups. The anthropometric values are reported in Table 1. Differences in gender and age between groups were not statistically significant ($p > 0.05$).

**Table 1.** Characteristics of the sample size (n = 262).

| | Ctrl (n = 88) | VO (n = 86) | Rt-Bf (n = 88) | BG |
|---|---|---|---|---|
| M – n (%) | 73 (82.9%) | 75 (87.2%) | 80 (90.9%) | p > 0.05 |
| F – n (%) | 15 (17.1%) | 11 (12.8%) | 8 (9.1%) | p > 0.05 |
| Age – mean years ± SD | 39.9 ± 7.5 | 39.9 ± 8.9 | 38.5 ± 8.2 | p > 0.05 |

Ctrl: control group; VO: video observation group; Rt-Bf: real-time biofeedback group; BG: between -group difference; M: male; F: female

In the jump protocol, the mean squat jump (SJ) post-intervention improved significantly in all three groups. However, the improvement in jump height in the Rt-Bf group (2.3 cm) was significantly higher (p < 0.001) than that in the other groups (Table 2).

**Table 2.** Jump protocol results

| Ctrl | | | | VO | | | | Rt-Bf | | | | BG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SJ (t0) | SJ (t1) | t1-t0 | p-value | SJ (t0) | SJ (t1) | t1-t0 | p-value | SJ (t0) | SJ (t1) | t1-t0 | p-value | |
| 29.1 [22.8-32.5] | 28.6 [23.85-33.8] | -0.4 [-0.5-2.05] | * | 27.7 [23.5-32.9] | 28.2 [25.3-35] | 0.8 [-0.7-2.7] | * | 27.2 [23.6-31.4] | 29.9 [25.5-35] | 2.3 [0.9-3.5] | * | ** |

Data are summarized as the median and interquartile range
t0: before-intervention test; t1: after-intervention test;
Ctrl: control group; VO: a video observation group; Rt-Bf: the real-time biofeedback group;
SJ: jump height (cm);
BG: between -group difference; *: p < 0.05; **: p < 0.001

In the balance protocol, the Rt-Bf group showed an improvement in almost all parameters, although these improvements were not statistically significant (Table 3).

**Table 3.** Balance protocol results

| Ctrl | | | VO | | | Rt-Bf | | | BG |
|---|---|---|---|---|---|---|---|---|---|
| EA (t0) | EA (t1) | p-value | EA (t0) | EA (t1) | p-value | EA (t0) | EA (t1) | p-value | |
| 35.9 [19.7-58.8] | 32.6 [20.1-55.2] | p > 0.05 | 25.3 [15.0-45.0] | 25.3 [16.7-40.8] | p > 0.05 | 29.8 [19.4-53.9] | 23.3 [15.5-42.5] | p > 0.05 | p > 0.05 |
| L (t0) | L (t1) | p-value | L (t0) | L (t1) | p-value | L (t0) | L (t1) | p-value | |
| 117 [97.1-147.3] | 116.5 [100.9-142.9] | p > 0.05 | 114.8 [94.9-146.4] | 103.4 [90.8-136.0] | p > 0.05 | 108.5 [90.0-153.0] | 113.4 [84.6-153.0] | p > 0.05 | p > 0.05 |
| MD (t0) | MD (t1) | p-value | MD (t0) | MD (t1) | p-value | MD (t0) | MD (t1) | p-value | |
| 0.89 [0.59-1.17] | 0.82 [0.64-1.18] | p > 0.05 | 0.72 [0.56-1.2] | 0.74 [0.58-1.0] | p > 0.05 | 0.8 [0.6-1.1] | 0.7 [0.6-0.9] | p > 0.05 | p > 0.05 |
| V (t0) | V (t1) | p-value | V (t0) | V (t1) | p-value | V (t0) | V (t1) | p-value | |
| 2.6 [2.2-3.4] | 2.6 [2.3-3.4] | p > 0.05 | 2.6 [2.1-3.4] | 2.3 [2.0-3.0] | p > 0.05 | 2.5 [2.0-3.4] | 2.5 [1.8-3.4] | p > 0.05 | p > 0.05 |

Data are summarized as the median and interquartile range
t0: before-intervention test; t1: after-intervention test; Ctrl: control group; VO: a video observation group; Rt-Bf: the real-time biofeedback group;
EA: ellipse area (cm2); L: length (cm); MD: mean distance (cm); V: velocity (cm/s);
BG: between-group difference

## Discussion

In this study, we evaluated performance improvement in balance and jump tests among 262 subjects. After receiving verbal instruction, the subjects were divided into three groups: one group received repeated verbal instruction, another received video instructions, and the third received visual real-time feedback.

Biofeedback has been used for many years in rehabilitation as an objective measure. Most biofeedback studies in the past have focused on the effects of this treatment on upper and lower-limb motor disorders in the neurological population [Jones & Beasley, 2015]. Rt-Bf has also been used in several studies [Smith et al., 2017] aimed at correcting knee alignment.

However, in recent years, the application of Rt-Bf has evolved, thanks to the increasing literature. Rt-Bf is now used in various healthy and injured populations [Palermi et al., 2022; Russo et al., 2020], as it allows athletes to quantify their progress, monitoring changes in real-time in the form of graphs, numbers, or animation on a screen. Using a sophisticated biofeedback apparatus, the psychophysiological responses of athletes can be measured before, during, and after an exercise, providing quantitative data necessary to assess performance. Biofeedback can also improve psychological health [Johnson et al., 2019], helping athletes lower self-reported anxiety, relax their muscles, and control their autonomic responses [Williams & Andersen, 2012]. Athletes are accustomed to receiving objective feedback on their athletic performance, and with Rt-Bf, they also have the opportunity to receive feedback about their physiological performance [Martin et al., 2018]. Therefore, it is a widely recommended tool in the preparation of an athlete to monitor and enhance overall performance.

The results of this study show a statistically significant improvement in the mean vertical jump height in all three groups. Notably, the difference between performance at the initial time point (t0) and the final time point (t1) in the Rt-Bf group was larger than that in the CTRL and VO groups. This suggests that Rt-Bf can modify a learning pattern from the first repetition, providing an advantage in the speed of learning, which, with repetition, develops the movement more rapidly. This is likely why the difference between the three groups is remarkable in the test used in the current research. This study's findings could have profound implications for the broader field of sports medicine and rehabilitation. If biofeedback can indeed lead to significant improvements in jump height and balance, it could revolutionize training programs for athletes and even non-athletes. The potential for injury prevention is also immense. By understanding their body better, individuals can make the necessary adjustments to avoid injuries.

On the other hand, we also observed an improvement in the Rt-Bf group with regard to the balance protocol, although this was not statistically significant. We concluded that Rt-Bf does not change balance performance in healthy subjects. However, other studies contradict this study's findings, showing the effectiveness of Rt-Bf in balance rehabilitation [Patterson et al., 2018]. Most of these studies have been conducted on a neurological population [Miller et al., 2019; Thompson et al., 2020; Lee et al., 2021], which might partially explain these different results. To the best of our knowledge, no studies have assessed an improvement in balance parameters after biofeedback training in healthy subjects. It is likely that these populations already have an adequate balance pattern, with less room for improvement; therefore, this type of training does not show significant improvement. Nevertheless, Rt-Bf training may still have potential benefits in healthy elderly subjects, where even minimal detectable improvements may have clinical significance. Indeed, for subjects with diabetes or neurological disorders, physical activity represents a cornerstone of their rehabilitation pathway [Gomez et al., 2022; Rodriguez et al., 2023], and the potential addition of Rt-Bf could play a pivotal role in improving their daily life activities. Moreover, the real-time data provided by biofeedback can be a game-changer in many medical scenarios. For instance, patients recovering from surgeries can benefit from understanding how their bodies are responding to various rehabilitation exercises. This can lead to more personalized and effective recovery plans. This could be a potential target for future studies.

This study did not include a long-term follow-up, which is a limitation because it is unclear whether the improvements observed are maintained over time. However, Barrios et al. [Barrios, Crossley, & Davis, 2016], in their study on gait analysis, showed that subjects retained the information learned and maintained the modified gait even at a one-month follow-up.

This could indicate that a systematic rehabilitation program with the inclusion of Rt-Bf may have long-term effects. We did not evaluate minimal detectable changes to confirm that the modification at t1 is related to our intervention and not to the repetition of the test itself. Because of the study setting and subjects' limited availability, we did not assess test-retest reliability. Finally, we did not compare other combinations of VER, VO, and Rt-BF. Future studies may consider performing VO and Rt-Bf simultaneously to evaluate potential improvements. Future studies could look into the effects of biofeedback on diverse populations, including different age groups and fitness levels. Additionally, the long-term effects of biofeedback-based training programs remain to be seen. It would be beneficial to understand if the improvements noted in this study are sustainable over extended periods.

## Conclusions

The insights gleaned from this study significantly underscore the transformative potential of integrating Rt-Bf in training regimes. Especially in athletic disciplines where jump performance is paramount, Rt-Bf could be a game-changer. The technological evolution promises a new era of sophisticated training, harnessing tools like Rt-Bf to optimize outcomes. While the current research did not unearth significant enhancements in balance for healthy subjects, the prospective benefits for populations with inherent balance impairments cannot be sidelined. Elderly individuals or those grappling with neurological ailments could immensely benefit from Rt-Bf, indicating its expansive scope beyond the realms of traditional athletic training. The burgeoning potential of Rt-Bf accentuates the need for continued exploration, ensuring its applications are both evidence-based and tailored to the diverse needs of different populations.

**Conflicts of interest** - None
**Author Contributions:** Conceptualization, F.S. and G.A.; methodology, E.K. and L.B. and D.T and L. B.; validation, I.I. and R.G.; formal analysis, D.Z.; investigation, L.R.; resources, A.D.; data curation, M.V.;

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**Data Availability Statement:** Under reasonable request, data are available to be consulted

**paraphrase:** None

**Acronyms**

EA: area, L: length, MD: mean distance, Rt-Bf: real-time biofeedback, SJ: jump height, V: velocity, VER: verbal instructions, VO: video observation

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