A literature overview of real-time biofeedback applications in sport and rehabilitation

Matevž Hribernik, Anton Umek, Anton Kos
University of Ljubljana, Faculty of Electrical Engineering, Ljubljana, Slovenia
matevz.hribernik@fe.uni-lj.si, anton.umek@fe.uni-lj.si, anton.kos@fe.uni-lj.si

***Abstract*— This paper presents a concise literature overview in the field of biofeedback applications and systems in sports and rehabilitation. We searched for papers in three research databases: Scopus, Web of Science, and PubMed. The initial search yielded 1728 papers. After a rigorous and exacting elimination process, 112 papers were finally included into this literature overview. We focused on full papers describing applications and systems with a complete real-time feedback loop, which includes the use of sensors (inertial, motion, force), real-time processing, and feedback to the user (visual, auditory, haptic). A number of research questions were raised and papers were studied and accordingly. We present the first results of this literature overview.**

Keywords: literature overview, real-time biofeedback, sensors, actuators, sport, rehabilitation

I. Introduction

Our research group has been studying and developing biomechanical biofeedback systems and applications for a number of years [1]. Recently, this research field has seen an increased popularity and we concluded that a systematic review of papers dealing with modern biomechanical biofeedback applications is necessary. Several reviews [2]–[4] discussing biofeedback applications can be found in accessible research databases. However, we were not able to find any that deals with the concept of biofeedback loop, its components and its operation. Usually, reviews focus on a single aspect of biofeedback: for example, only on the acquisition of the signals and data from sensors or only on the feedback type and use. There are also a very limited number of reviews written from a technical or an engineering point of view. All of the above has motivated us to conduct this study.

Every biofeedback system or application consist of four main interconnected entities: user, sensor(s), processing unit and actuator(s). Sensors are usually attached to the user performing an activity or integrated into specialized sport equipment. Sensors are used to collect variables about users' movement. Sensors are wired or wirelessly connected to the processing unit that analyses and processes sensor data depending on the application. The processing unit also prepares and sends the feedback information to the actuator. Actuators, that can be either visual, auditor or haptic, present the feedback information about the movement to the user. The user utilizes the received feedback to alter the movement to be in-line with the desired task, thus closing the feedback loop.

Our primary objective was to learn about the types of biofeedback applications and systems other research groups have developed and what were their building elements, operation principles and functionalities. We conducted a short survey of resent developments in biofeedback applications in sport [5] where we dealt primarily with pilot studies presented in conferences. During this study we were found only one systematic review that deals with technical (engineering) aspects of biofeedback [2]. Others were mainly concerned with study protocols related to sport or rehabilitation science, or with different sensor uses, in particular [3], [4], [6]–[8].

Due to the extent of the field, we focused only on real-time biomechanical feedback systems, as those systems are the current the challenge in the design of the state-of-the-art solutions. Such systems can be used in the field of sports or physical rehabilitation. For the user, to receive, understand and accept the feedback as concurrent, the system must operate in real-time. Due to the human nature, latency between the movement and feedback is related to human senses and feedback modality [9].

To create a literature overview, we defined a set of important aspects and properties of biofeedback systems. Based on this set, we raised a number of research questions against which we tested all papers included into this literature overview:

- What kind of sport or therapy is being performed?
- Which sensor or system is used to capture motion?
- Number of sensors used and their placement?
- Is sensor fusion used?
- What type of communication is used?
- Processing and communication architecture?
- What type of modality is used for the feedback?
- Who is the primary user of the system?

Due to the nature of this paper we present preliminary results of our broader and ongoing research, this means that only certain aspect of the given research questions is presented.

This paper is further structured as follows, in section 2 we present methods of research, in section 3 we present results, and in section 4 we conduct a short discussion of the results, we conclude with section 5.

II. Methods

To conduct this literature overview we searched three well-known research databases: Scopus, Web of Science, and PubMed. We used the search string to include as many papers as possible fitting our study:

```
(Sensor* OR System* OR Application*) AND
(Kinematic OR Inertial OR Motion OR  Force
OR Pressure OR Accelerometer OR Gyroscope
OR Strain*) AND (Feedback OR Biofeedback)
AND (realtime OR "real time" OR real-time
OR concurrent OR Instant) AND (Sport* OR
Rehabilitation)
```


The search yielded 1728 papers: 676 papers on Scopus, 660 on Web of Science, and 392 on PubMed. After removing duplicates and conference proceedings, 1062 papers remained. The entire search procedure is shown in Figure 1.

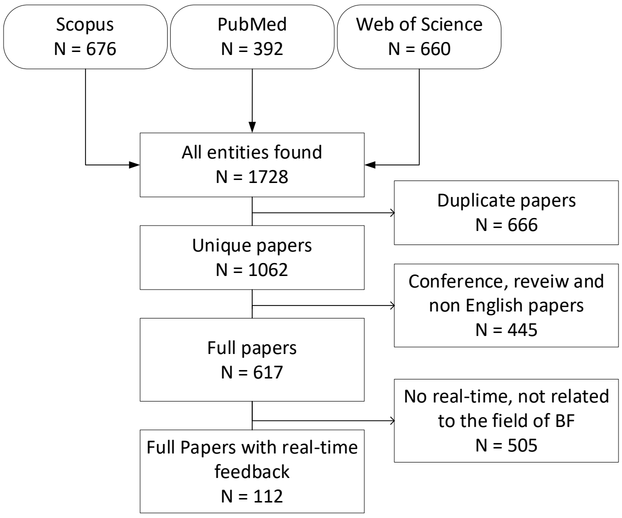

Figure 1. Workflow when conduction a search. From all papers to full papers with real-time feedback.

TABLE I.
NUMBER OF PAPERS FROM DIFFERENT DATABASES AFTER DUPLICATES REMOVAL. PAPERS FROM MULTIPLE SOURCES ARE ALSO SHOWN.

Databases	Number of papers
PubMed	116
Scopus	227
Web of Science (WoS)	228
Scopus + PubMed + WoS	140
Scopus + PubMed	62
Scopus + WoS	217
PubMed + WoS	72
Total	1062

Later, we removed all non-English papers, systematic reviews, conference papers, and one video; 617 papers remained. We used a more detailed paper keyword search to find papers with specific content that directly fitted our study. We removed all papers from the fields of medicine (surgery), robotics, prosthetics, work-related, or papers dealing with physiological parameters of the user (heart rate, EEG, etc.) or papers that deal only with trivial sensor measurements (pedometers). After careful reading, we found out that some papers did not implement real-time paradigm and were therefore excluded as well.

Finally, we were left with 112 papers that describe applications implementing a complete feedback loop, use appropriate sensors for motion acquisition, process the sensor signals and data in real time, and provide real-time feedback to the user. Those 112 papers were evaluated according to the presented research questions. They are collated into different categories, according to application, feedback modality, sensor types, communication technology, and users.

III. RESULTS

Final 112 papers are all from the field of real-time biofeedback; they all research and study different aspects of biofeedback. We were strict when assessing the papers, that only papers with full feedback loop and real-time operation are included and studied. We present findings after careful reading of all papers included in this literature overview.

A. Application field

On the grounds of the paper's application field, we divided them according to two criteria: (a) does the paper study sport or rehabilitation activity, see Figure 2 and (b) what is the actual activity being performed when receiving feedback, see Figure 3.

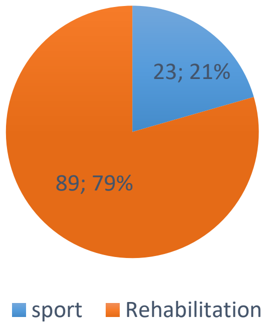

Figure 2. Papers according to the main activity. In cases, when application can be used in both groups the main usage is taken.

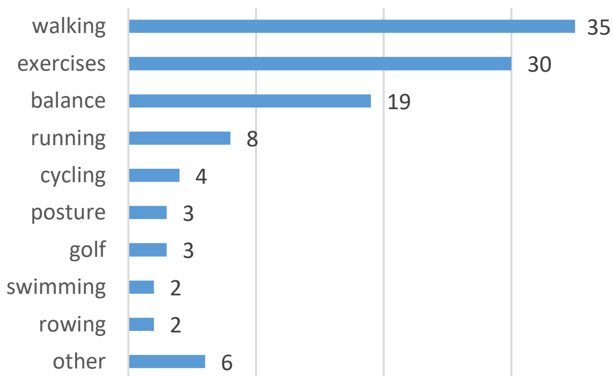

Figure 3. Final papers according to subcategories of activity. Both sport and rehabilitation are main activity in some subcategories (walking, exercises, and balance).

It can be observed that only one fifth of all papers dealt with sport activity and all the rest with rehabilitation. A more precise activity categorisation shows that most of the biofeedback systems are employed in relatively simple motion tasks, such as walking. Some of those activities are exclusively part of a rehabilitation therapy, while others are a type of sport being performed. Walking, exercises and balance can be part of both basic categories, but are mostly represented in rehabilitation paper group. Exercises that are part of rehabilitation are understood as exercises performed with a therapist. They usually include a specific limb or body movement that is a part of the therapy. Those that are a part of a sport, include various physical exercises for training.

B. Feedback modality

One of the main functionalities of every biofeedback system is its ability to return the information about the performed action back to the user. As this can be achieved using different actuators, we defined high-level groups that are human sense specific. This yields visual, auditory and haptic feedback interface that use vision, hearing and touch as modalities. We studied modalities used in papers; results are shown in Figure 4. Some studies use more than one modality. Researchers predominantly utilize visual modality; 62 papers used exclusively that modality, while 19 more used visual modality with either auditory or haptic or both. Two papers used all three modalities, and no papers utilized haptic an auditory exclusively.

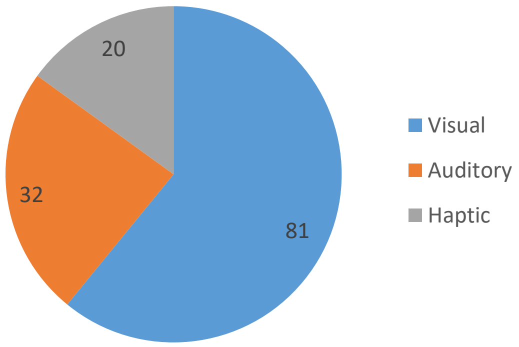

Figure 4. Papers divided according to different feedback modalities. Some systems and researchers use more than one modality simultaneously, or test different modalities for similar application.

C. Sensors and measuring systems

Different researches use different sensors or sensor systems for the evaluation of kinematic parameters. We combined sensors in generalized groups, even if physical implementation varies; we present findings in Figure 5. Inertial Measuring Unit (IMU) is the most represented sensor, followed by force sensors that are divided into force plates and force/pressure sensors. Optical motion capture systems are used in 14% of papers (17) as the main measuring device connected to the feedback application. It should be noted that similar systems are used in other papers as a reference or as part of the validation of other measuring systems. Other miscellaneous sensor types are used in 15% of the papers (cameras, goniometers, encoders, optical fibre sensors). IMU in this case represents all the papers that utilize general components of the IMU, this means accelerometer, gyroscope and magnetometer in any of the combinations.

Sensor placements are presented in Figure 6. Different applications require different sensor locations on a human body. However, there are a large number of cases where the sensor is not attached to the body but integrated into sport equipment. The "N/S" group covers: optical tracking system, cameras, force plates, etc. The most common place for sensor attachment is: legs, back or feet. Only a small number of papers have sensors located on any other part of the body. In addition, four papers use full body-tracking using different solutions (HTC Vive controllers and trackers, custom fiber optic and kinematic sensors and commercial TMA devices). A well know wearable commercial motion tracking system Xsens is used in seven studies, but only for partial body tracking. Sixteen reviewed papers that use sensor fusion were also found.

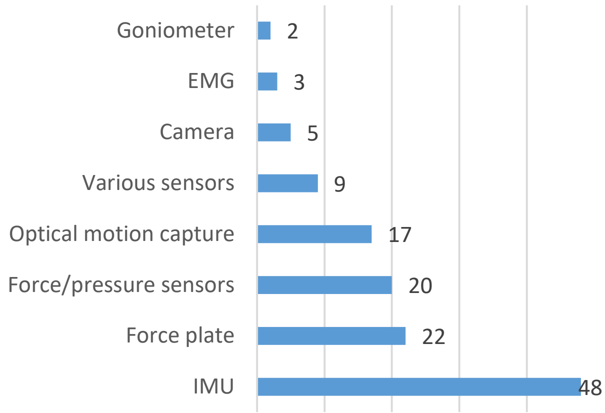

Figure 5. Sensors used in different biofeedback applications, some papers utilize more than one type of sensor. If multiple sensors of the same type are used in a single study they are presented only once.

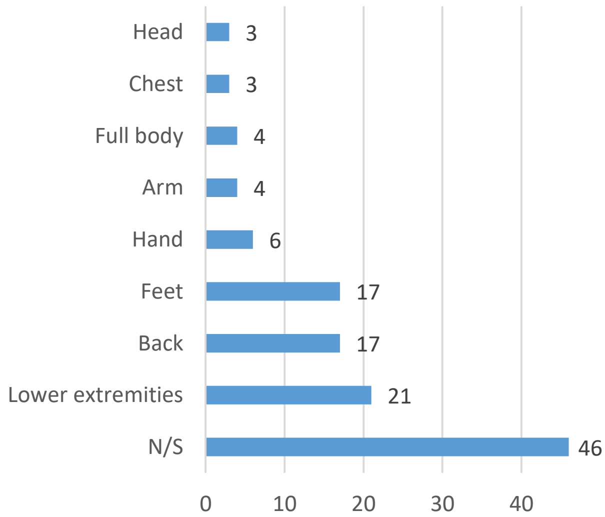

Figure 6. Sensor body mounting location. Some papers with multiple sensors use several locations. N/S (Not specified) can be used in multiple cases where sensor is not attached to the user person, or different techniques are utilized.

D. Communication

The type of communication is specific to sensor or actuator design and application requirements. We are interested especially in the type of communication used between sensor and the processing device and between the processing device and the actuator, what is shown in Figure 7.

We are interested in the most used communication technologies between devices. Wireless communication is used with most wearable devices; wired sensors are rarely used with them. Wired sensing component is in most cases not attached to the user, but is a part of external sensing equipment; we denote this scenario as a "system". Optical motion capture systems, thread mills with force sensors all fall under this category.

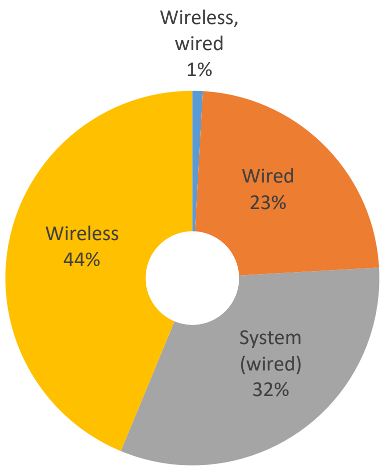

Figure 7. The most important communication technology used in systems and applications. Categories apply to sensors, actuators, or both, depending on their use.

E. Operation and users

In biofeedback systems, we can distinguish between two main users than usually interact with each other: (a) the user interacting with sensors denoted as user (athlete, patient), (b) expert user denoted as professional (trainer or therapist).

When conducting a survey we made a distinction between systems where the main user is a person interacting with sensors (user in a loop) and where the main user is an expert (professional). We show results in Figure 8. The distinction should be made between a person receiving a feedback (user in a loop) and a main user. Professional category (72% of papers) generally uses a complex system that requires an expert to setup and work with the user and a system. User category (18% of papers) includes simpler studies and applications that can be operated by non-expert users. Some research includes both paradigms. Professional systems are normally a part of a research environment (laboratory, hospital, gym), while user systems are usually wearable systems, which do not require special setup and can be used without expert knowledge.

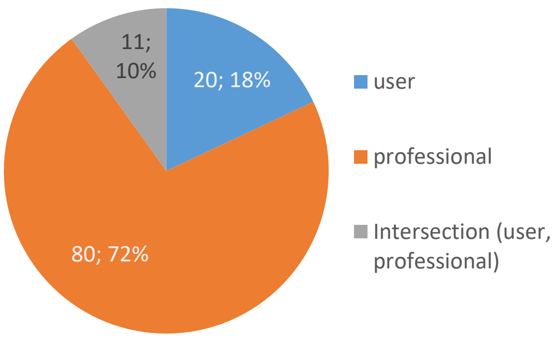

Figure 8. Main users of the system are the one that will most likely use the system, not the one receiving the feedback.

IV. Discusion

The large number of papers found in the three databases was mainly the consequence of a search string that includes keywords that are common in several research fields, not just the field of biofeedback. This made our work more difficult in the later analysis; we can say this distinguishes our literature overview from others that started with fewer papers. Finally, we use 112 papers to examine the field of real-time biofeedback and answer the raised research questions.

We found out that the majority of papers are from the field of physical rehabilitation, only the minority of papers are from field of sport. This is not surprising as the implementation of real-time feedback is easier to implement on a specific (repetitive) movement used in rehabilitation than on a complex movements in sport. This point is emphasized by a fact that out of 112 papers 35 deal with walking action and gait rehabilitation. As this is a well understood repetitive motion, it is not difficult to give users a useful concurrent feedback.

When discussing the use of feedback modality, Figure 4 does not show the entire truth. As many different actuators fall under the same type of feedback modality, but the user experience is completely different depending on the feedback actual device. There are a large number of different kinds of visual actuators: projectors, screens, VR headsets, AR headsets, smartphones, and tablets. Screens are the most used feedback modality. In eight papers, they used some kind of VR/AR solution, which is the currently the most advance way of giving feedback. We can also consider the difference in research and development of the system with VR/AR technologies and a simple computer display feedback. However, this does not correlate to the usability and user friendliness of the system. Other feedback modalities, auditory and haptic, have less available actuators. Auditory actuators are: headphones, speakers and buzzers, haptic actuators are: vibro-tactile devices and electro stimulators. Unlike visual actuators, these have less significant difference in user experience.

Sensor types are the most diverse category. We divided them into logical groups and their use is connected to the type of communication used in the system. The predominant sensor is kinematic sensor (IMU) and its components, accelerometer and gyroscope. In more than 70% of the cases, the authors specified that they use a wireless device with integrated kinematic sensor attached to a body. The opposite is true when it comes to force and pressure sensors. Only 25% of those studies utilize wireless technology. They use force and pressure sensors inside insoles, and measure walking parameters. Force plate and optical motion capture fall under the system (wired) category and there are numerous different biofeedback applications that are using these systems.

We differentiate between users of the system. In all researches, a person in a loop (athlete, patient) receives the feedback during the activity; meanwhile some professional can receive information about that person’s activity. However, the person in a loop can operate the system or that is done by someone else. That is why we differentiate between systems that are designed for professional studies, and those that are developed for general population usage. From our findings, it is clear that few research groups work on systems that deal with self-sufficient user-centred applications.

V. Conclusion

In this short literature overview, we look into the field of real-time biomechanical feedback systems and applications in sport and physical rehabilitation. After a search of three databases (PubMed, Web of Science, Scopus) we found 1062 unique papers. After applying the inclusion criteria, we ended up with 112 full papers. Papers are arranged according to five categories: application, modality, sensors, communication, and users. Similarities between papers were observed. Reviewed papers show the potential for future development and research. Most of the papers provide a proof of concept and user studies of biofeedback applications and concepts in the field of sport and rehabilitation, there is still space for engineering, design and technological improvement.

Acknowledgment

This work is sponsored by the Slovenian Research Agency within the research program *ICT4QoL - Information and Communications Technologies for Quality of Life* (research core funding No. P2-0246) and within the bilateral project between Slovenia and Serbia titled Sensor technologies as support systems for the detection and selection of talents in sport and monitoring the performance of athletes (research core funding No. BI-RS/20-21-023).

References

[1] A. Kos and A. Umek, *Biomechanical Biofeedback Systems and Applications*. Springer, 2018.

[2] R. Li, D. T. H. Lai, and W. Lee, 'A Survey on Biofeedback and Actuation in Wireless Body Area Networks (WBANs)', *IEEE Reviews in Biomedical Engineering*, vol. 10, pp. 162–173, 2017, doi: 10.1109/RBME.2017.2738009.

[3] C. Z.-H. Ma, D. W.-C. Wong, W. K. Lam, A. H.-P. Wan, and W. C.-C. Lee, 'Balance Improvement Effects of Biofeedback Systems with State-of-the-Art Wearable Sensors: A Systematic Review', *Sensors*, vol. 16, no. 4, Art. no. 4, Apr. 2016, doi: 10.3390/s16040434.

[4] O. M. Giggins, U. M. Persson, and B. Caulfield, 'Biofeedback in rehabilitation.', *J Neuroeng Rehabil*, vol. 10, no. 1, p. 60, Jun. 2013, doi: 10.1186/1743-0003-10-60.

[5] M. Hribernik, A. Umek, and A. Kos, 'Survey of recent development in real-time biofeedback systems in sport', *Serb J Sports Sci*, vol. 2020, no. 11(1), pp. 19–28, May 2020.

[6] C. Agresta and A. Brown, 'Gait Retraining for Injured and Healthy Runners Using Augmented Feedback: A Systematic Literature Review.', *J Orthop Sports Phys Ther*, vol. 45, no. 8, pp. 576–584, Aug. 2015, doi: 10.2519/jospt.2015.5823.

[7] J. J. Tate and C. E. Milner, 'Real-time kinematic, temporospatial, and kinetic biofeedback during gait retraining in patients: a systematic review.', *Phys Ther*, vol. 90, no. 8, pp. 1123–1134, Aug. 2010, doi: 10.2522/ptj.20080281.

[8] X. Zhang, G. Shan, Y. Wang, B. Wan, and H. Li, 'Wearables, biomechanical feedback, and human motor-skills' learning & optimization', *Applied Sciences (Switzerland)*, vol. 9, no. 2, 2019, doi: 10.3390/app9020226.

[9] C. Attig, N. Rauh, T. Franke, and J. Krems, 'System Latency Guidelines Then and Now – Is Zero Latency Really Considered Necessary?', May 2017, pp. 3–14. doi: 10.1007/978-3-319-58475-1_1.