Haptic user interface for biofeedback in aquatic sports: A design concept

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

***Abstract*— This paper focuses on a problem of providing real-time biofeedback to a swimmer through a haptic user interface. This interface is integral part of a special wearable device that can be used during swimming. Wearable devices have been proved to be very efficient for providing feedback during various activities, including sports and particularly swimming. We considered several modalities for this interface and finally decided for the haptic modality as it has not been studied in this context before and can, according to our experiences, provide promising results. The proposed haptic biofeedback interface consists of a wearable device attached to the swimmer's lower back and equipped with sensors, a processor, and vibrotactile motors in the belt. The selected hardware configuration allows multiple modes of operation depending on the requirements of the biofeedback application. The wearable device is designed to be part of a larger biofeedback system or to be operated independently.**

Keywords: haptic, user interface, feedback, modality, vibrotactile, water sport, wearables

I. Introduction

Human motion is studied by the field of kinematics and is quite well researched. Various sensors can be used to measure and evaluate human motion and their use has been studied extensively. Biomechanical biofeedback on the other hand is a rapidly developing area of augmented learning in sport and rehabilitation. The use of wearable devices and systems in professional and recreational settings is also increasing. Any useful biofeedback system consists of at least a user, a sensor, a processing device, and an actuator [1]. The basic idea of biomechanical biofeedback is to provide a user in motion with additional information about their movement that he or she cannot detect with his or her own senses. Figure 1 shows the basic idea of biomechanical feedback: during the user's physical activity, sensors are attached to the user's body or sports equipment to detect, record, and measure motion parameters. The data from the sensors is sent to the processing device where it is processed and converted into useful information that is presented to the user through the selected actuators. This allows the user to adjust and change their movement to improve their abilities or health. We conducted a research and found out that there is a lack of studies using new and unique actuators for providing feedback in various sports. Wearable devices with actuators therefore present a big opportunity for new studies [2]. Feedback information provided to a sportsmen should be meaningful and understandable and should depend on the type of presentation and selection of the senses it should stimulate. There are three different types of basic senses and feedback modalities: visual, auditory, and haptic. For example, screens or displays provide visual feedback, headphones and speakers provide auditory feedback, while vibrotactile motors or electrical stimuli provide haptic feedback. The complexity of the information that can be provided to the user depends on the selected modality and also user's experience and knowledge.

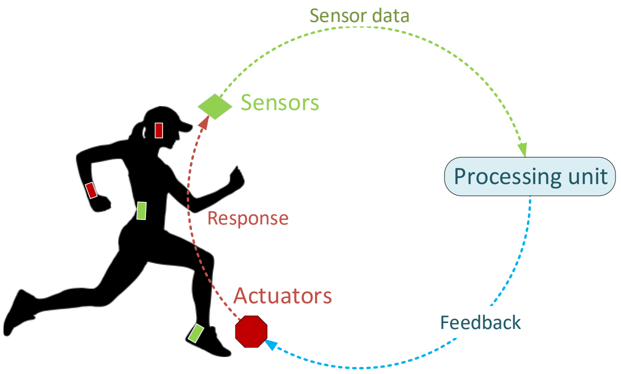

Figure 1. Biomechanical biofeedback loop. Sensors measure user's movement, and the data from these sensors is processed and prepared for feedback in a processing unit. The feedback is presented to the user in different modalities using actuators. The feedback loop is closed when the user responds with the change in their motion based on the information provided by the actuators. This research addresses the design process of a haptic user interface with vibrotactile actuators.

Our previous experience with biofeedback has shown us that auditory and haptic feedback are most useful for simple wearable devices, while visual feedback is more appropriate for various head mounted displays. For outdoor activities, the auditory or haptic feedback seem better options as we need our visual sense to orient ourselves in the environment. Auditory and haptic information can therefore still be perceived without interference [2].

The development in this area, driven by our research and others, motivated us to develop a novel concept for a wearable device with actuators for aquatics that can be used in other areas. The lack of wearable feedback devices, especially those that work in water, also motivated us. This makes this project a novel and unique research effort. The main research goal of this project focuses on the ability to provide feedback to the swimmer through an appropriate modality, initially by developing a haptic user interface. We have designed a concept and simple prototype for a wearable device that can provide real-time haptic feedback to a swimmer. Our research group has already studied swimming motions and different swimming techniques [3]. As a next step in developing a real-time biomechanical feedback application, we are interested in providing relevant real-time feedback to the swimmer. With this knowledge, we now need to design and implement a haptic user interface that can provide feedback to the swimmer using vibrotactile actuators on the user's lower back. This paper provides a summary of the design process and concept for developing a haptic user interface for real-time feedback.

This paper is structured as follows, in Section 2 we present related work in the field of biomechanical feedback applications, particularly those dealing with aquatic activities. In Section 3, we present the design process for a haptic user interface, reviewing other studies with similar ideas and how they relate to our design. In Section 4, we discuss our design and present possible future studies and modifications. We conclude with Section 5.

II. RELATED WORK

The main challenge in developing biofeedback applications is to provide relevant and useful feedback to the user and to select the most appropriate modality, as various options may be considered in similar studies. Three modalities are available, but their efficiency and appropriateness varies from application to application. This is because not every situation and activity is appropriate for all modalities. Applications in water present an additional challenge, as many devices that normally work outdoors do not work in water. Some actuators also produce different stimuli underwater.

We have already seen some studies and designs for underwater sports by other authors, but they mostly use the visual modality [4]–[6] and auditory modality [7], [8]. Gandolla et al. [4] present a full body suit with integrated sensors and visual feedback placed on the screen out of the water. Their study is primarily based on rehabilitation exercises in water, and therefore visual feedback is sufficient. They use a display to show the user the representation of their body position and provide instructions for exercises in the water. Santos et al. [5] primarily focus on a device with underwater kinematic sensors and LoRa communication, but also incorporate haptic actuators into the device. They provide visual feedback from the user to the trainer, but also envision the possibility of providing simple haptic feedback to the user. This idea and implementation is not described in detail in the paper. Kos et al. [6] present a basic concept for therapists working with patients or coaches working with athletes in an aquatic environment. Important parameters that can be obtained from sensors regarding different swimming techniques are presented.

In turn, Cesarini et al. [7] present a wearable swimming device equipped with pressure sensors and headphones to provide real-time auditory feedback during swimming. They use sonification to convert sensor data into sound, allowing athletes to modify their behaviour while swimming. Similarly, Schaffert et al. [8] present a wearable device with an integrated kinematic sensor that can provide auditory feedback to the swimmer using sonification. They systematically test different types of feedback to the user, distinguishing between continuous and discrete sonification. The results show that athletes and coaches prefer the discrete sonification, yet this is an ongoing study.

In our experience, in the desired aquatic environment, only solutions with both sound and vibration stimuli could be useful for real-time use. We anticipate that both would be difficult to implement in an aquatic environment. While other authors have shown that auditory feedback is feasible underwater [7], [8], we are mainly interested in the other option that we consider suitable for deployment, i.e. designing and creating a haptic feedback device.

Haptic user interfaces are regularly used in biomechanical feedback applications, although their use is less common than visual and auditory [2]. We first examined the designs of haptic feedback interfaces proposed by other authors. Two interesting studies [9], [10] implemented haptic feedback for users during walking. Both studies use haptic interfaces on both legs to provide users with information about their walking symmetry. They use a vibration motor on each leg to implement the feedback. In [9], they use a combined main unit with controller and wire connection to each motor. In contrast, Chen et al. [10] use a wireless haptic ankle bracelet with four vibration motors. They implement feedback based on multiple stimulation points, which makes it possible to provide multiple types of feedback to the user, unlike [9] where they could only stimulate amplitude at a single point. With multiple motors, different feedback patterns can be generated to provide multidimensional information to the user.

Haptic feedback has also been used to improve aerodynamics in cycling [11], using a single vibromotor on the user's upper back. Haptic feedback has also been used in rowing training [12] in conjunction with other modalities.

An interesting concept was recently presented by Ashapkina et al. [13]. They created a user interface with haptic feedback using multiple vibromotors in the form of a wristband. The presented device includes kinematic sensors, wireless communication, and a haptic feedback interface. This enables a new way of interacting with the user by using haptic ques. They enable feedback interaction by using various amplitudes, frequencies and patterns of vibrations of haptic actuators.

During the design process we have also studied how to assess cyclic nature of motion during swimming [3], [6]. From this study, we can obtain imporant variables and paterens found in different swimming techniques and use this knowledge, as well as the findings from the studies that use auditory feedback, to develop a haptic feedback system for a swimmer.

III. DESIGN PROCESS

The main component of the proposed system with haptic feedback is the sensor device with microcontrollers and kinematic sensors which we have already used in previous studies [3]. We upgraded this wearable device by including also wireless communication and vibrotactile motors for feedback.

After carefully reviewing related studies, we were able to determine the main concept and building blocks of our design. Since we wanted to provide feedback during various water activities, especially swimming, this limits the ability to attach the wearable device to the user. Our initial sensor device was designed to be attached to the waist using a swim belt [3], [6], and the goal was to further improve this design. The natural progression was to incorporate actuators into the swim belt, as shown in Figure 2. In our design we mainly follow the approaches of Ashapkina et al. [13] and Chen et al. [10], who use multiple haptic actuators arranged as a band around the wrist or ankle. We propose to add an array of six vibrotactile actuators to the existing swim belt with sensors. The actuators will be placed on the inside of the belt to provide the best possible contact with the skin. It is important that the connections, actuators, sensors and processing device are all waterproof.

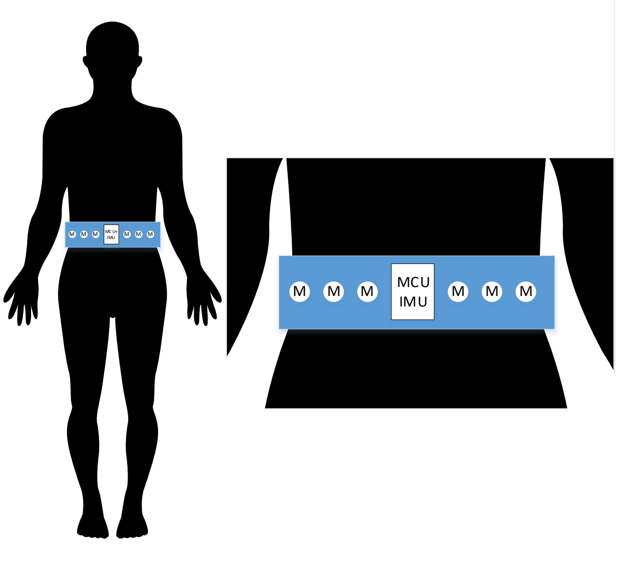

Figure 2. Swimming belt location on a lower back of an athlete. The control circuit and sensors are placed in the center, and there are three (3) vibration motors on each side. This makes it possible to provide real-time feedback to the swimmer.

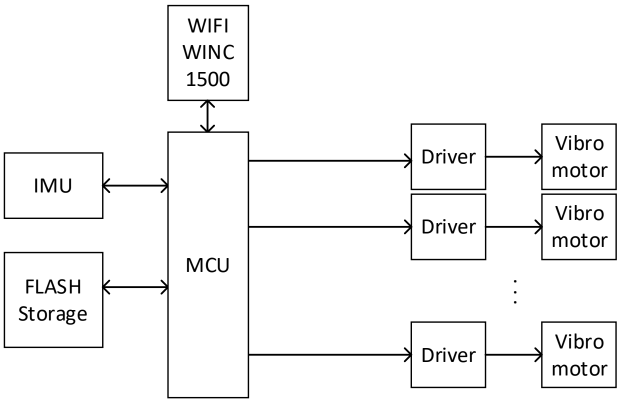

Figure 3. Architecture of the wearable feedback device. The Adafruit Feather M0 microcontroller board is connected to the wireless module, kinematic sensors, and external memory. The microcontroller also provides inputs to the drivers that drive the vibromotors. Each motor is controlled independently.

Our design is based on the Adafruit Feather M0 microcontroller board [14] in combination with kinematic sensors [15], [16] (inertial measurement unit - IMU) and independently controlled vibration motors for feedback. The architecture of our controller is shown in Figure 3. We have also included the possibility of an external memory unit in the form of flash memory. This type of design architecture allows for variable operation, either as an offline or online sensor/actuator device. With this wearable device, it is possible to measure and process motion and to provide feedback using a standalone and simple application environment on a device. On the other hand, it can also be connected to a more advanced processing device (e.g. powerful computer) using communication between wearable device and computer.

The initial prototype of feedback device is presented in Figure 4. Vibration motors, three on each side of lower back, are connected to the central box, that includes other components: controller, sensors and drivers. Drivers are connected to the microcontroller inside the watertight box while each driver is further connected with a selected motor using two wires. Individual motors are amplitude-controlled, it which enables also control of motor intensity, oscillation frequency and generation of different patterns. Motor vibration intensity is controlled using PWM (pulse-width modulation) enabling slight and powerful operation. The changes in the current of the vibromotor change the rotation frequency that is then sensed as a vibrating intensity. By cycling over various intensities and distinct actuators this enables the change in oscillations of the motors as well as providing the user with distinguished patterns that can be used as feedback information.

Figure 4. Pre-prototype of the wearable haptic interface for biomechanical feedback. The top image shows the exposed vibromotors with connections to the main control unit. Each motor is connected separately to the control unit. The bottom image shows the final sealed design ready for testing.

IV. Discousion

Our wearable feedback interface is intended to be part of a larger and more complex swim feedback system or application. This wearable haptic user interface is designed to be flexible and work in different environments to detect motion and provide feedback information to the user. In this concept research, we focus on the implementation of the hardware and the design of the feedback interface, as shown in Figures 2-4. We acknowledge that the design is similar to that of a wearable tactile device from [13]. However, we used their design to develop a different and new device that is capable of providing feedback in aquatics, which would not be possible with their device. Figure 4 shows the feedback device in a preliminary version. In developing this haptic feedback, we were particularly concerned that each vibromotor could be controlled independently. This allows the development of applications where both a position of the actuator on a body and an amplitude of the vibration can provide unique feedback information to the user. It is also possible to generate a sequence of events and variable amplitudes to create patterns with even more inherent information value.

This is the first time this type of haptic user interface is being proposed as feedback device in biomechanical feedback applications for various sports. This makes our research comprised of multiple parts and studies. One of the first challenges is to prove that the haptic interface is capable of providing some type of feedback to athletes at all. This means designing and developing a wearable haptic interface usable in different feedback environments. Initially, the haptic interface must be tested with users in a normal (dry) environment. Users must be able to distinguish between different actuators, amplitudes, and patterns for this interface to be viable. This initial test will include multiple professional athletes; they will wear this feedback on their back while being stationary. The device will be connected to the controller using wireless communications, allowing for direct control of the presented vibrations. The subjects will be exposed to multiple intensities of each motor and combination of several motors. The goal to test whether users can distinguish between actuator's locations and changes in, their vibration Finally, users should distinguish different vibration patterns, frequencies, and intensity on multiple locations. They will also going to determine their appreciation of presented feedback from their in-depth knowledge as athletes. Sport trainers will also be asked for their expert opinion. The knowledge and results from this study will be a starting point for all other studies with users.

The second step in the development of this haptic interface is to conduct a similar usability test in an aquatic environment, both in the stationary mode and during physical activity. This test will allow us to evaluate the effectiveness of the proposed haptic user interface in the real environment: We know that a haptic interface can be perceived differently when users are physically active or when they are not moving.

The final phase of testing this haptic user interface will be the implementation of rudimentary biofeedback, with the use of onboard sensors and processing device. These tests are similar to those in [8], where the auditory interface was tested with sonification of kinematic sensor data. The differences between continuous and discrete sonification were tested. Similarly, we propose to test the haptic interface by performing a simple conversion from sensor data to a haptic interface. We believe this provides a fair comparison between haptic and auditory feedback in swimming.

After all these tests the proposed haptic interface can be used in complex biofeedback applications [6]. Multiple sensors are used both on the user's body and in the pool, and feedback can be generated based on multiple external sensors and factors including the coach's ability to intervene. This design concept allows us to develop different applications for swimming, both for motor learning and professional training. The hardware is generally the same in both cases, while only the signal processing and algorithm requirements have to change for different applications.

We are also aware that our design has some limitations that may need to be addressed in the future. Currently, we have designed the belt with six uniformly distributed vibration motors. Future studies may show that a different arrangement of actuators would be beneficial to the user. Right now, the actuators are only placed on the user's back. There is a possibility that positioning these actuators on the front of the waist would be beneficial to the athlete. It could also be beneficial to have more actuators placed on the waist. The current design is also not designed for the high stress that is expected during swimming, so other materials will be needed in the future to build this haptic user interface.

V. Conclusion

In this paper, we present a process of designing a concept for a haptic feedback interface that can be used in biomechanical biofeedback applications. We carefully studied the hardware designs and operation of various feedback devices and interfaces presented by other authors. This knowledge enabled us to design a feedback concept that can work in our desired environment, i.e. aquatic sports. We also built a preliminary prototype that has limited capability and is specifically intended for early testing. Future testing is needed to learn about the limitations of this particular design. In the future, this type of haptic feedback interface may be used in sport training, recreational swimming, and aquatic rehabilitation as a building block of a more complex biofeedback application.

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