Smart equipment design challenges for feedback support in sport and rehabilitation

Anton Umek, Anton Kos, and Sašo Tomažič
Faculty of Electrical Engineering, University of Ljubljana
Ljubljana, Slovenia
anton.umek@fe.uni-lj.si, anton.kos@fe.uni-lj.si, saso.tomazic@fe.uni-lj.si

***Abstract*—Smart equipment can support feedback in sports training, rehabilitation, and motor learning process. Smart equipment with integrated sensors can be used as a standalone system or complemented with body-attached wearable sensors. The first part of our work focuses on real-time biofeedback system design, particularly on application specific sensor selection. The main goal of our research is to prepare the technical conditions to prove the efficiency and benefits of the real-time biofeedback when used in selected motion-learning processes. The tests performed on two prototypes, smart golf club and smart ski, proves the appropriate sensor selection and the feasibility of implementation of the real-time biofeedback concept in golf and skiing practice. We are confident that the concept can be expanded for use in other sports and rehabilitation.**

***Index Terms* — smart equipment, motor learning, sport, rehabilitation, biomechanical biofeedback**

I. Introduction

Feedback is the most important variable for learning except the practice itself [1].

During the practice, the natural (inherent) feedback information is provided internally through human sense organs. Augmented feedback is provided by external source, traditionally by instructors and trainers. Modern technical equipment can help both the performer and the instructor. In many sports disciplines video recording is a classical method for providing additional feedback information for post analysis and terminal feedback. Modern technical equipment can provide more precise measurements of human kinetics and kinematics parameters and can considerably improve the quality of feedback information. Modern optical motion tracking systems are using passive or active markers and several high-speed cameras. An alternative to optical tracking systems are inertial motion unit (IMU) based systems, which use several wearable sensors attached to the human body. Both types of motion tracking systems are professional and expensive equipment that can be used not only for biomechanics research in sports, rehabilitation and ergonomics but also as an animation tool in movie industry and virtual reality tracking. Augmented feedback supported by technical equipment (sensors and actuators) is defined as biofeedback because a human is inside the feedback loop. The general architecture of a biofeedback system is presented in Figure 1.

To achieve a widespread use of biofeedback applications, important feedback information concerning knowledge of performance should be provided with less complex and cheaper technical equipment. Miniature IMU sensors (accelerometers and gyroscopes) are integrated in every modern smartphone. Consequently, many motion activity applications for smartphones and wearables using only accelerometer data exist.

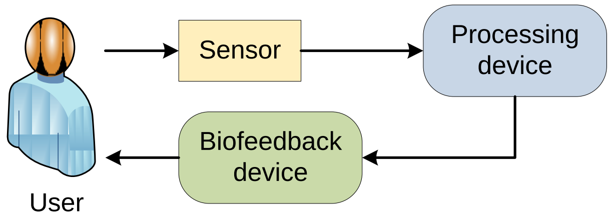


Figure 1. General architecture of a biofeedback system.

In many sport disciplines and rehabilitation scenarios various types of equipment is essential or even indispensable for performing the desired task (tennis rackets, baseball bats, golf clubs, alpine skis, stretching devices, crutches, etc.). In fact, in the most relevant human actions are transferred through the equipment. All this equipment can be supported with different types of sensors, not only accelerometers, gyroscopes and magnetometers. For example, strain sensors are the perfect choice to detect and measure force, torque, and bending in different parts of the equipment. An appropriate sensor fusion algorithm can give precise information on performers' actions and equipment reactions. A feedback from the sport equipment could therefore improve the performer's skills, especially if it is provided in real-time, that is, without a significant delay.

Sport equipment companies have already started embedding the digital technology into their products. Some examples of smart sport equipment, which are already available on the global market, are: smart shoes, smart tennis racket, smart basketball, smart baseball bat, and smart golf clubs [2]. In the near future it is possible to predict many improvements in technology that could drive down the prices and encourage a widespread adoption of smart sport equipment.

II. Motivation

In majority of research work in sport and rehabilitation wearable sensors are used for the purpose of monitoring and post processing signal and data analysis. The feedback information is given with delay after the performed activity, what is defined as terminal feedback. The same is true for the majority of sport and healthcare applications already available on smartphones; post processing with presentation of some vital or important parameters. The concurrent feedback, which is given in real time within the currently performed action, is very useful for motor learning, but is not frequently used.

The primary aim of our research is the development of technical equipment that would allow implementation of real-time biomechanical biofeedback systems. We are convinced that such systems would allow a leap in research in this field. The important tasks in our research are the selection of appropriate sensors and the assurance of suitable conditions for sensor signal transmission and processing. As it is evident from research papers, IMU sensors are the most often used sensors in golf and skiing [3][3]-[10]. The principles of sensor signal fusion are similar in the fields of sport training, rehabilitation, and biomedicine. The main focus of our current research is **motor learning in sport with the help of feedback** information provided by sensors integrated into sport equipment. The results of our research are easily implemented also in the field of rehabilitation equipment as motor learning in rehabilitation is generally less demanding from that in sport.

III. Sensors in Smart Sport Equipment

The integration of sensors into sport and rehabilitation equipment enables the acquisition of information about motion, static positions, and acting forces. Using the sensor signal analysis and specific a priori knowledge, the validation of the movement correctness can be achieved and appropriate feedback information can be communicated within the biofeedback loop. This procedure was tested in practical experiments in the field of training in golf and alpine skiing. For the validation of the above presented concept, we developed two original smart equipment prototypes: smart golf club and smart ski. Based on first measurement results we have started with the development of real-time biofeedback system usage concepts and procedures. They include a systematic approach by defining the useful short practice lessons, adapting the precision of real-time biofeedback system to the capabilities of the user (amateur vs. professional), the choice of correct feedback modality, and the appropriate amount of feedback information adapted to the limited perception capabilities of users during training.

IV. Smart Sport Equipment Protoypes

During our research we have developed two fully functional smart sport equipment prototypes; smart golf club and smart ski. We present their properties and field test results in the following subsections.

A. *Smart golf club*

The smart golf club prototype includes: (a) two strain gage sensors, which measure the golf club shaft bend and (b) 3-axis MEMS accelerometer and 3-axis MEMS gyroscope, which measure acceleration and angular speed of the golf club. The latter two sensors are a part of the independent Shimmer 3 IMU equipped with Bluetooth communication interface. Strain gage sensor signals are acquired by the National Instruments cRIO professional measurement system with module 9237.

Shimmer 3 device can reliably stream sensor data up to sampling frequencies of 512 Hz, which was used in our experiments. The accelerometer's dynamic range is up to ±16 g_0 and the gyroscopes dynamic range is up to ±2000 deg/s. The precision of both is 16 bits per sample. In the experiments the Shimmer 3 device is fixed to the club's shaft just below the grip as seen in Figure 2.

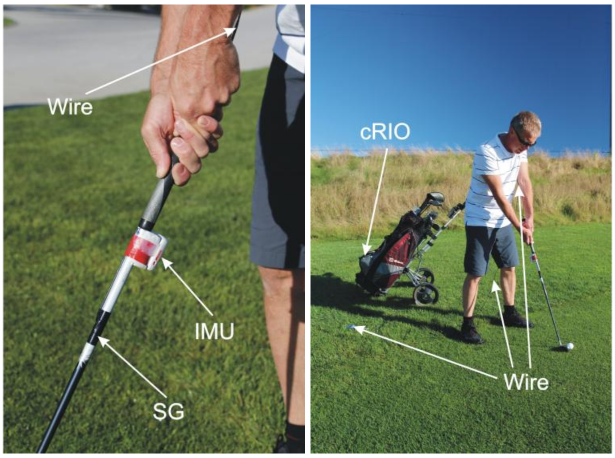
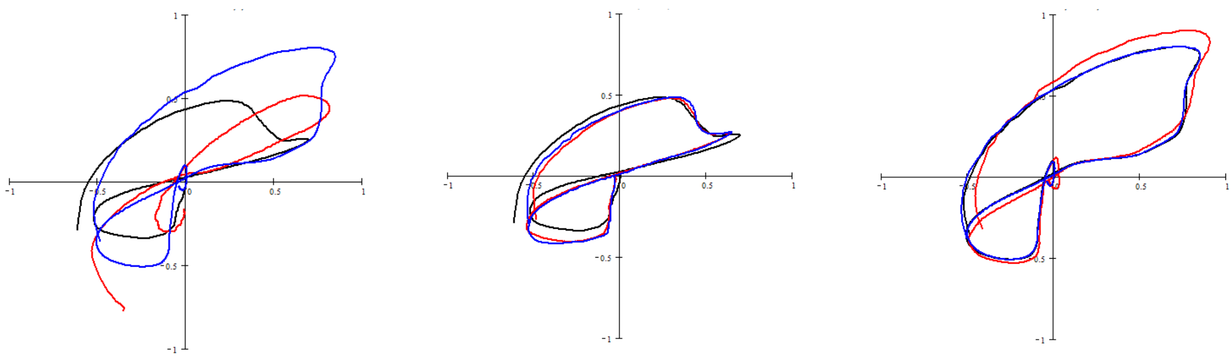


Figure 2. Smart club prototype used in field.

Sensor signals are synchronized and processed by the distributed LabVIEW™ application running on the laptop and cRIO platform. After streamed sensor signals are aligned by their impact samples, they are segmented into separate swings, each containing 1500 samples, with impact sample at index 1000. At the sampling frequency of 500 Hz the duration of each swing is 3 s. In the graphs presented in this paper we plot only swing signal samples between indexes 250 and 1000 or 1.5 s time frame.

Figure 3 shows the player signatures produced by the two strain gage sensors orthogonally placed on the shaft of



(a) (b) (c)

Figure 3. Smart golf club prototype includes a 2D bending sensor; its trajectories confirm high consistency of players swings. Average trajectories (N=10) show (a) large differences between three different players' signatures, and much smaller differences between the perfect swing and faulty swings of the same player (b) and (c).

the golf club. Figure 3(a) shows trajectories (signatures) of a perfectly performed straight swing of three different players. We see that their signatures are distinctively different. Figures 3(b) and 3(c) show the trajectories of different swing types of player 1 and player 3 respectively. It can be seen that the differences in trajectories of the same swing type of different players is greater than the difference in trajectories of the different swing types of the same player.

Figure 4 shows the sensor signals with marked points in time that correspond to the distinctive phases of the golf swing. Sensor signals are acquired by two strain gage sensors (top graph), 3-axis accelerometer (middle graph), and 3-axis gyroscope (bottom graph). Trajectories show high consistency of swings, repeatability, and precision of the measuring system.

(a) address (b) takeaway (c) backswing (d) top of the bsw (e) downswing (f) impact

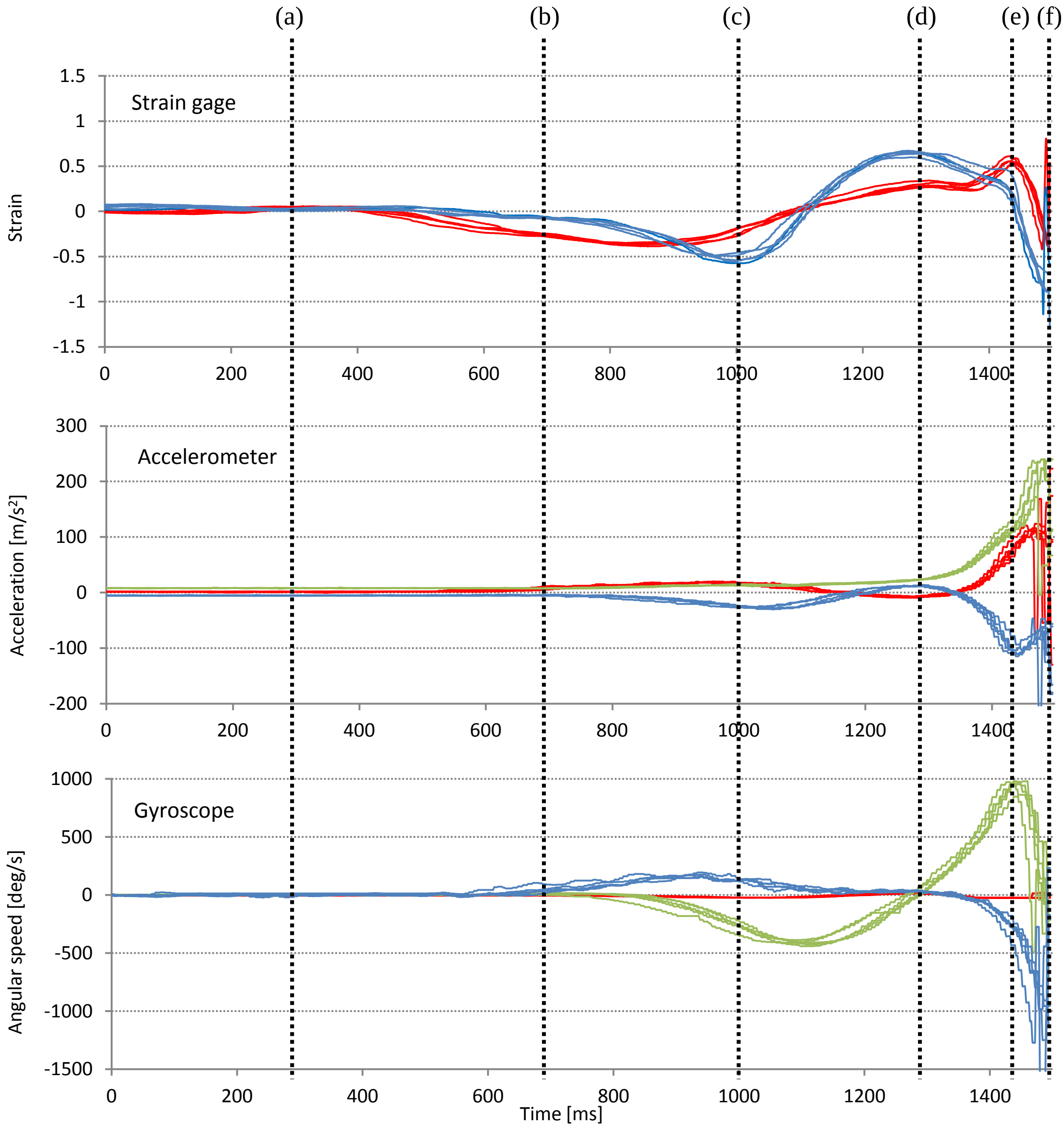


Figure 4. Sensor signals and phases of the swing: (a) address, (b) takeaway, (c) backswing, (d) top of the backswing, (e) downswing , (f) impact.

B. *Smart ski*

Smart ski prototype includes strain gage sensors for measuring the bend of the ski in several sections of the ski, several force sensors for measuring the force that the skier is applying to the ski, 3-axis accelerometer, and 3-axis gyroscope for measuring the motion. Bend and force sensors are integrated into the ski, accelerometer and gyroscope are attached to the skier's torso. The prototype is shown in Figure 5; Smart skis are shown in the left hand side and the fully equipped skier to the right hand side of the figure.

Sensor signals are collected, synchronized and processed by the LabVIEW™ application running on cRIO platform from National Instruments. The sampling frequency of the system is 100 Hz. The accelerometer's dynamic range is up to ±16 g_0 and the gyroscopes dynamic range is up to ±2000 deg/s.

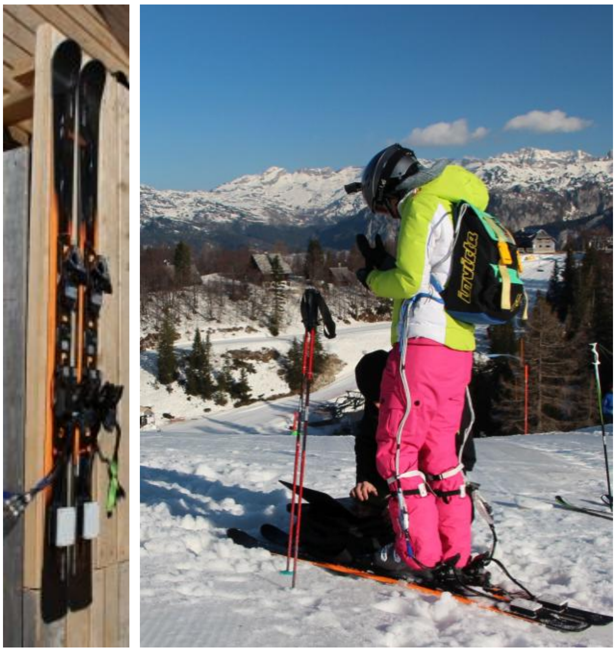


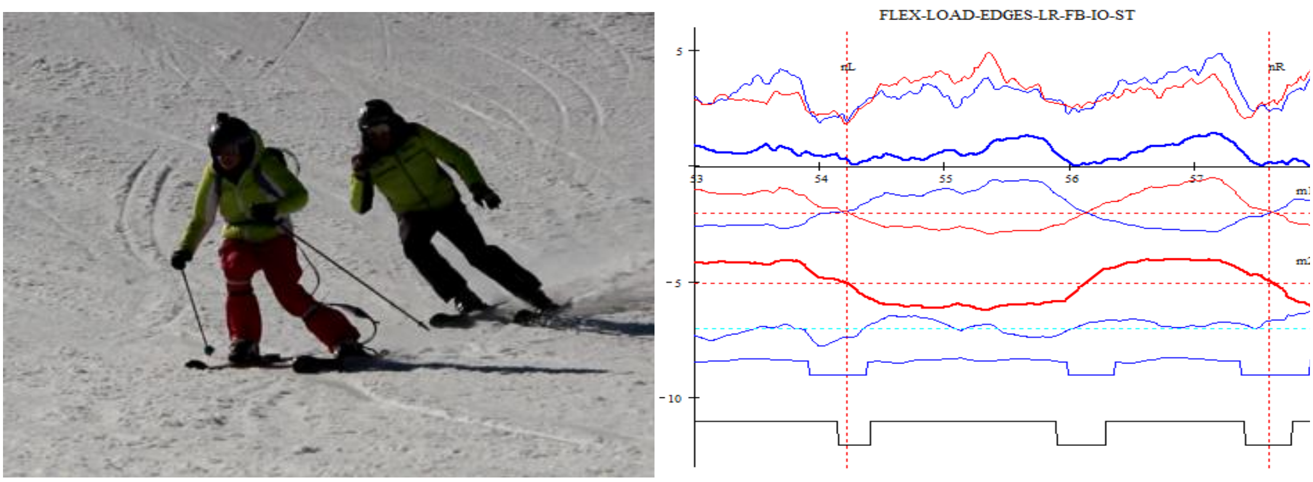
Figure 5. Smart ski prototype.

Laboratory tests for equipment operation testing, calibration and validation were followed by several snow tests in different weather and snow conditions and performed with different expert skiers, some ex world cup racers and some from the Slovenian Alpine Demo Team. Test skiers performed various skiing tasks and techniques according to the predefined schedule.

For example, one of the tasks was to perform the carving turns by equally loading both skis. Figure 6(a) shows the test skier during testing and Figure 6(b) the corresponding signals acquired during the test. Observing from top to bottom, Figure 6(b) is showing the following signals and calculated plots: a pair of signals shoving the bending of the left and right ski, total dynamic load applied to both skis (thick blue line), a pair of plots showing the load on the left and right ski edges, relative load balance in the left-right direction (thick red line), relative load balance in the front-rear direction, relative load distribution on the outer ski, Boolean steering phase indicator (black line).

The final goal of the research is the development of the user application with real-time biofeedback. The feedback can be given through different modalities. An example of a real-time visual feedback, projected onto the skier's goggles, is shown in Figure 7. The exemplary display includes the binary state indicators (carving) and sliders showing skiers current performance (outer/inner).

Figure 7. Real-time biofeedback application.



(a) (b)

Figure 6. Skiing experiments with smart ski prototype and the corresponding signals and calculated plots.

V. Conclusion

We show the most important results of experimenting with both presented prototypes: smart golf club, smart ski. With the smart golf club prototype we have shown that the differences in trajectories of the same swing type of different players is greater than the difference in trajectories of the different swing types of the same player. With the smart ski prototype we can precisely and timely measure the action of the skier and the reaction of the skis and terrain at the same time. The acquired information from the integrated sensors is used in the testing of ski performance and for ski technique improvement or learning. The developed application allows the ski expert to analyze the performance of the skier based on several measured and calculated parameters. The application is currently capable of recognizing different phases of carving technique and diagnoses typical errors in regard to the load distribution during the steering phase of the turn.

Based on first measurement results we have started with the development of real-time biofeedback system usage concepts and procedures. They include a systematic approach by defining the useful short practice lessons, adapting the precision of real-time biofeedback system to the capabilities of the user (amateur vs. professional), the choice of correct feedback modality, and the appropriate amount of feedback information adapted to the limited perception capabilities of users during training.

References

[1] Bilodeau, E. A., Bilodeau, I. M., & Alluisi, E. A. (1969). Principles of skill acquisition. Academic Press.

[2] Lightman K. Silicon gets sporty. IEEE Spectrum. 2016 Mar, 53(3), 48-53, DOI: 10.1109/MSPEC.2016.7420400.

[3] Nam, C. N. K., Kang, H. J., & Suh, Y. S. (2014). Golf swing motion tracking using inertial sensors and a stereo camera. IEEE Transactions on Instrumentation and Measurement, 63(4), 943-952.

[4] Betzler, N. F., Monk, S. A., Wallace, E. S., & Otto, S. R. (2012). Effects of golf shaft stiffness on strain, clubhead presentation and wrist kinematics. Sports biomechanics, 11(2), 223-238.

[5] Ueda M, Negoro H, Kurihara Y, Watanabe K. Measurement of angular motion in golf swing by a local sensor at the grip end of a golf club. IEEE Transactions on Human-Machine Systems. 2013, 43(4), 398-404, DOI: 10.1109/TSMC.2013.2266896

[6] Michahelles, F., & Schiele, B. (2005). Sensing and monitoring professional skiers. IEEE Pervasive Computing, 4(3), 40-45.

[7] Kirby, R. (2009). Development of a real-time performance measurement and feedback system for alpine skiers. Sports Technology, 2(1-2), 43-52.

[8] Nakazato, K., Scheiber, P., & Müller, E. (2011). A comparison of ground reaction forces determined by portable force-plate and pressure-insole systems in alpine skiing. J Sports Sci Med, 10(4), 754-762.

[9] Nemec, B., Petrič, T., Babič, J., & Supej, M. (2014). Estimation of alpine skier posture using machine learning techniques. Sensors, 14(10), 18898-18914.

[10] Yu, G., Jang, Y. J., Kim, J., Kim, J. H., Kim, H. Y., Kim, K., & Panday, S. B. (2016). Potential of IMU sensors in performance analysis of professional alpine skiers. Sensors, 16(4), 463.