A real-time interactive biofeedback system for sports training and rehabilitation

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Abstract: Biofeedback systems have become a prominent component in the sports domain as a means of motor training and rehabilitation. This paper presents the development of a biofeedback prototype and system software framework facilitating its functionality in real time. The prototype incorporates an inertial measurement sensor unit, a wireless vibration stimulus module for vibrotactile biofeedback, and interactive system software behaving as the backbone of the system. The functionality of the prototype was tested with a stability test during which biofeedback was provided to improve postural control based on trunk tilt displacements. The test involved subjects standing in the tandem Romberg position during which their medial–lateral trunk tilt was measured, and postural sway biofeedback was conveyed via vibrotactile actuators placed on either side of the trunk. Two conditions were tested, namely eyes open and eyes closed, and postural sway with biofeedback was evaluated, as opposed to with no feedback. A 15.2 per cent sway reduction resulted in the eyes-open condition, and a significant reduction of 55.2 per cent was reported for the eyes-closed condition. The results demonstrate that instantaneous feedback provided via vibration stimulus can reduce postural sway based on trunk tilt measurements. Hence, the system's pertinence to comparable approaches employed in sports training and rehabilitation is foreseen.

Keywords: inertial sensors, virtual instrumentation, vibrotactile biofeedback, sports training, motor augmentation

1 INTRODUCTION

Sports biomechanics have gained high popularity with the recent technological developments in smart wearable devices and intelligent systems. Biomechanical analysis has become a vital tool for sports professionals, coaches, and athletes in order to maintain consistency in performance and health. The ultimate goal of biomechanical analysis in sports is to improve techniques and to prevent or reduce the risk of sports injuries [**1**]. The variety of biomechanical devices and systems has diversified immensely from ground-based systems, body-mounted devices to comprehensive virtual-reality-based training systems. Typical illustrations of such systems for sports analysis involve the use of accelerometers for upper-extremity lawn bowling analysis [**2**], smart floor development for ground reaction force measurements [**3**], vision-based systems for badminton, golf swing, walking, and karate movement [**4**, **5**], and a combination of sensor and vision technology for soccer gait recognition [**6**]. Morizono *et al.* [**7**] and Hamalainen *et al.* [**8**] proposed virtual-reality-based sports training for 'playing catch' and martial arts. The use of such systems has contributed to the improvement in sports performance, detection of improper movements, identification of injury prevention techniques, and long-term examination of sports movements.

However, in spite of the functionality employed in performance analysis systems, coaches and athletes using such systems receive feedback on their performance only once the training sessions are completed. Revisiting one's own performance is beneficial to learn and to identify improper techniques in particular sports movements, but feedback received after the training sessions may constrain an individual's ability to employ proper techniques accurately dur-

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ing training. In addition, post-training feedback will not have any impact on detecting improper postures during a performance, which may lead to sports injuries.

Biofeedback systems in this regard play an important role in facilitating constructive real time feedback for augmenting motor performance during sports training. A biofeedback system can be effectively utilized to monitor an individual's performance constantly and to provide immediate response on performance statistics. Sports professionals and trainers use biomechanical analysis to understand injury mechanisms, to evaluate clarity of technique, and to provide effective training protocols for performance improvements [**9**]. Real-time biofeedback devices complement the trainer and the trainee during their performance by providing immediate feedback on technique and injury-prone movements based on the measurement parameters through which trainees are continuously acknowledged to modify their movements.

A biofeedback system typically incorporates a sensory device, a restitution device that can convert the biofeedback information to the subjects, and a processing system that can perform computations, decision making, and control of the input–output devices in the system [**10**]. Restitution mechanisms involve devices that produce auditory, visual, or tactile feedback to the users in response to their measured movements.

Many researchers have utilized auditory restitution mechanisms for immediate biofeedback, e.g. jump landing [**11**], balance monitoring [**12**], and weight shifting during golf training [**13**]. Auditory signalling is utilized as the means of indicating the measured movement in correspondence to a target value in these systems. Similarly, the use of visual biofeedback for stability training and home-based physical activity monitoring has been presented in references [**14**] and [**15**]. The efficacy of tactile biofeedback systems in the sports domain has been emphasized by many researchers. Tactile feedback systems exist in electrotactile, thermal, and vibrotactile modalities [**16**]. The concept of tactile technology is based on the skin's ability to communicate information through these modalities. Opposed to auditory and visual feedback, tactile feedback is a more suitable modality for sports applications, as visual and auditory feedback can interfere with a subject's visual or acoustic dependence for different tasks and can restrict the use of such systems on blind or deaf individuals. In tactile systems, electrotactile and thermal feedback can cause pain and fatigue on the skin. In comparison, vibrotactile systems are proven to be safe on human skin and have the ability to decipher feedback information in a simple, realistic manner. This was further acknowledged by Lieberman and Breazeal [**17**] with the development of a wearable vibrotactile robotic suit that can be used to imitate a teacher's motion on a novice to assist in learning new movements. They reported that the inclusion of the robotic suit resulted in an accelerated learning rate of 23 per cent. The significance of direct positional vibrotactile feedback for reducing the heart rate while optimizing the performance of rowing – as opposed to direct non-positional and delayed feedback – was discussed in reference [**18**]. Vibrotactile feedback has resulted in a significant heart-rate drop ($p < 0.02$), which is in contrast with the increase in the heart rate reported with other feedback conditions. It was suggested that intuitive localized feedback cues can reduce the effort invested by rowers to maintain a good rowing technique. Sergi *et al.* [**19**] presented an interesting approach which highlighted the impact of visual and vibrotactile (visuotactile) feedback as a guiding modality for a positioning task and claimed that visuotactile feedback reported a statistically significant ($p < 0.01$) accuracy over visual feedback. Similar approaches were discussed in references [**20**] to [**22**]. The versatility of vibrotactile feedback systems proven from the above research studies provide evidence that athletes and sports trainers can benefit from instantaneous assistive feedback to optimize performance.

Physical training that challenges postural stability has become a prominent component in sports as an important element in injury prevention and athletic performance improvement. The significance of stability tests for sports and rehabilitation was highlighted in reference [**23**], for the evaluation of sports aptitude and pathology. Lamoth *et al.* [**24**] interpreted the evaluation of athletic skill level based on postural sway measurements obtained using trunk acceleration during a stability test. Balance control during walking gait for athletes and non-athletes following concussion was discussed by Parker *et al.* [**25**]. McGuine and Keene [**26**] presented the impact of balance training programmes to reduce the risk of ankle sprains in soccer and basketball athletes. Comparable balance assessments were illustrated in references [**27**] and [**28**], highlighting the importance of postural control and its impact on normal daily activity, motor skills, and pathology. Such balance assessments and training programmes can benefit from the inclusion of biofeedback during sports training and rehabilitation procedures. A biofeedback system could be used to provide immediate information on improper movements or to define specific training targets during physical training. In addition to coach feedback, athletes can benefit from a real-time biofeedback system during sports training procedures to optimize performance, to reach training goals more rapidly, and to reduce the risk of injury due to improper movements.

In this regard, this paper presents the development and evaluation of a real-time biofeedback prototype providing biofeedback based on trunk tilt measurements obtained during the tandem Romberg stability test. Subsequent sections illustrate in detail the hardware–software co-design, experimental method, results, discussion, and conclusion.

2 SYSTEM ARCHITECTURE

The development employed an inertial measurement sensor unit (IMSU) for angular measurements, a simple web camera for video recordings, a real-time interactive hardware–software co-design which behaved as the backbone of the system, and a stimulus module for vibration feedback. The system software facilitated the acquisition of data in real time from the IMSU, data validations, graphical representation of movements, and generation of real-time biofeedback. Feedback activation was performed on the basis of a target threshold boundary utilized in the experiments. Each angular displacement record was compared against the target range and, if a boundary violation was detected, vibrotactile feedback commands were generated on the basis of the extent of the violation. The commands were transmitted to the vibrotactile control circuit over a radio-frequency (RF) medium to activate the corresponding vibrotactile actuators (VAs) with the corresponding pulse rate. The pulse rate of the VAs related to the extent of the boundary violation. Concurrently, the violations were depicted via a visual display available on the interface.

Options were provided in the system interface to save the video and kinematic data obtained during tests. The system included a database repository implemented using Microsoft Structured Query Language (MS SQL) that facilitated subject details and test session records that could be revisited for comprehensive analysis. Figure 1 illustrates the system architecture.

2.1 System hardware

The system hardware incorporated a wearable IMSU mounted on the trunk, a vision module, and a wearable vibrotactile feedback unit with VAs placed on either side of the trunk for medial–lateral (ML) sway feedback.

2.1.1 Wearable sensors

Microstrain's triaxial inertial measurement unit was used in this study. The unit has a compact size of 41 mm × 63 mm × 24 mm and a mass of 39 g, which are ideal features for wearable applications. The IMSU supports the measurement of a variety of kinematic parameters including acceleration, velocity, Euler angles, and angular rate. Each IMSU involves a base station that connects to the host computer for wireless data transferring. This study utilized Euler angle measurements for the generation of biofeedback. The IMSU supports a full 360° measurement of orientation ranges over all axes with a resolution of less than 0.1°, an accuracy of ±0.5°, and data rates of up to 250 Hz over a sensor bandwidth of 1–100 Hz. The on-board processor handles compensation for sensor misalignments, gyro *g* sensitivity, and gyro scale factor non-linearity.

2.1.2 Vision module

A simple web camera from Creative (VF0080) with a USB interface was used for video capture of the tests performed. The capture speed of the web camera is 30 Hz. When a training session was started, the video capture was initiated, and the user was given the

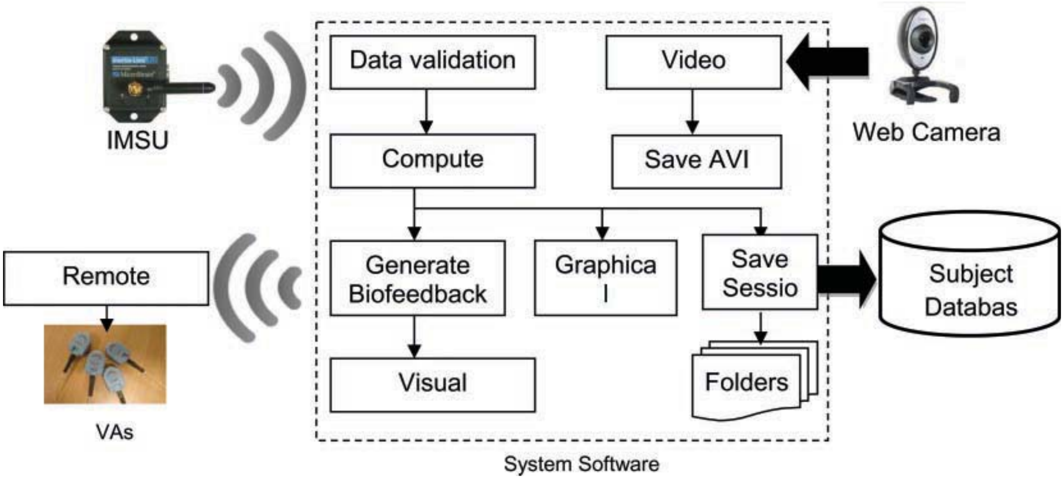


Fig. 1 System architecture

option to save the captured video as AVI files if required.

2.1.3 *Biofeedback control circuit development*

A biofeedback control circuit was built into the system to receive commands wirelessly from the host computer for activating the VAs. The circuit involved Cypress CY8C27443 8-bit microcontroller, an RF transceiver (ER 400TRS), audio amplifiers (MC34119) that behaved as motor drivers for the VAs, VBW32 VAs, and 9-V batteries for the power supply. An RF transceiver unit interfaced via a serial line to the host computer wirelessly transmitted the biofeedback commands to the control circuit. The microcontroller was programmed to listen continuously to incoming commands and to activate the corresponding VA with the corresponding pulse width modulation.

The VAs employed in this development are Tactaid VBW32 from Audiological Engineering Corporation, USA, which are small lightweight elements that produce a vibration when powered. The VBW32 has a resonant frequency of 250 Hz which is ideal for recognition on human skin, and it has very high ring-up and ring-down times which makes it ideal for real-time feedback.

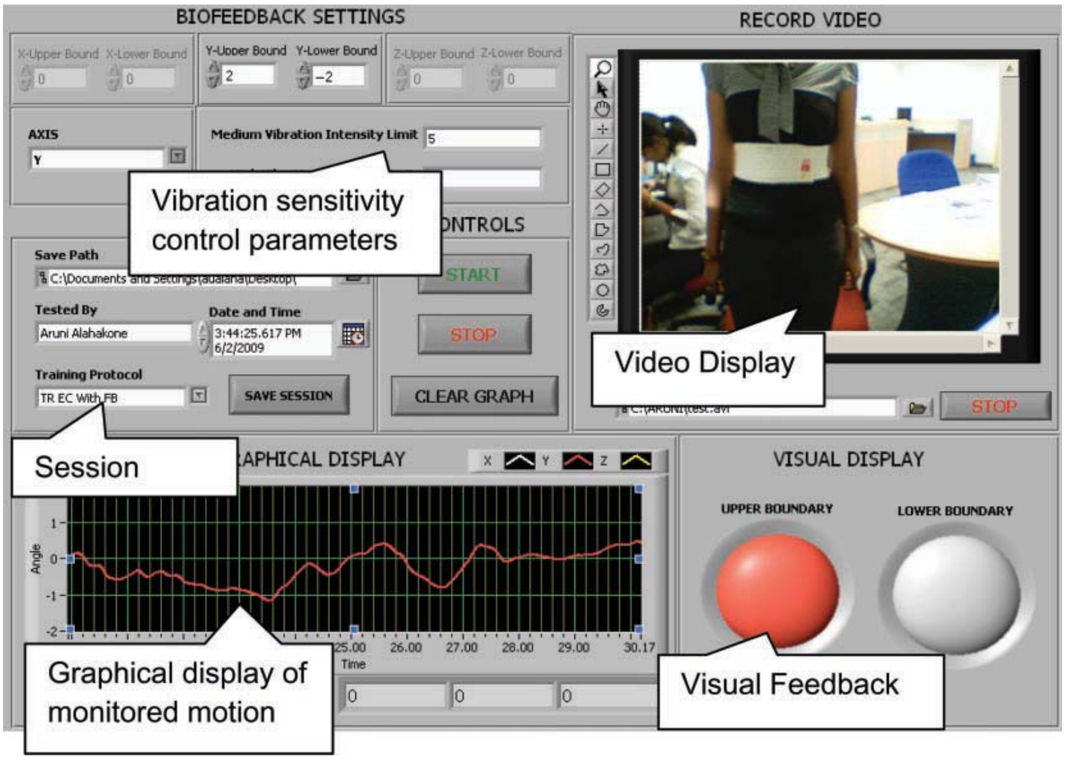
2.2 System software

The system software was developed using the LabVIEW virtual instrumentation software platform; it performs the hardware configurations, data acquisition, data validation, biofeedback activation based on selected thresholds, and graphical representation of experimental data in the system. In addition, subject data management and data storage facilities were incorporated. Brief descriptions of the user interface attributes and feedback generation scheme are given in the subsequent sections.

2.2.1 *Interactive graphical user interface*

Subject information management, hardware device recalibrations, feedback reconfigurations, real-time data visualization, and post-test data analysis tools were integrated into a single user interface, providing users with system customizability and ease of human–computer interaction. A database built using MS SQL facilitated the subject and test session information. System hardware calibration tools were embedded to perform sensor connectivity verifications, sensor alignments, and connection establishment with the remote feedback unit. The software tools dedicated for data acquisition and biofeedback signalling are depicted in Fig. 2.

With regard to the experiment to be conducted, movement axis, thresholds, and biofeedback sensitivity limits can be configured. When a test was initiated, angular measurements acquired from the IMSU were produced for users via the graphical



X-Upper Bound: 0
X-Lower Bound: 0
Y-Upper Bound: 2
Y-Lower Bound: −2
Z-Upper Bound: 0
Z-Lower Bound: 0
AXIS: Y
Medium Vibration Intensity Limit: 5
Save Path: C:\Documents and Settings\adalana\Desktop\
Tested By: Aruni Alahakone
Date and Time: 3:44:25.617 PM 6/2/2009
Training Protocol: TR EC With FB
C:\ARUNI\test.avi

Fig. 2 Motion monitoring and feedback tools display in real time. Concurrently, the web camera attained video capture of the tests being performed.

Formulation of feedback was based on the angular measurements received. This parameter allowed the generation of feedback signals with respect to the defined threshold range. In synchrony, variations from the threshold range were conveyed to the system operators via a simple visual display, indicating both the direction and the magnitude of the violation.

2.2.2 *Biofeedback generation*

The generation of biofeedback followed a stepwise scheme defining the bandwidth during which no feedback is delivered (dead zone) and the consequent stepwise increase in vibration strength as the angular measurements move further away from the dead zone. Figure 3 depicts the continuous increase in pulse rate starting at 0 per cent within the dead zone, and switching to 20 per cent, 50 per cent, and 80 per cent with the progressive increments in the angular measurements. In this manner, directional information was conveyed via activation of the VA referring to the corresponding direction, and the amplitude was conveyed via the pulse rate variations of the VAs.

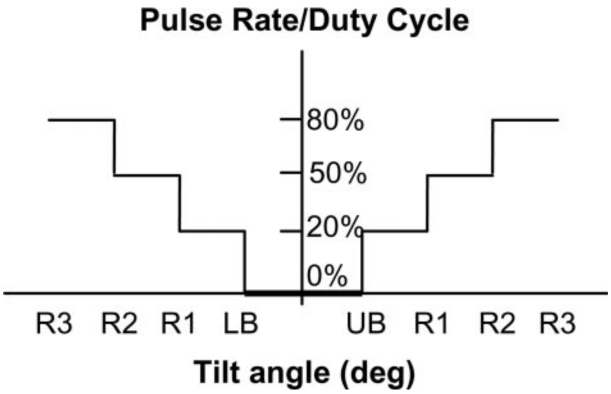


Fig. 3 Relationship between the tilt angle and the tactile feedback command generation. UB and LB refer to the upper bound and the lower bound respectively and correspond to the threshold limits pertaining to the dead zone. R1, R2, and R3 represent the vibration sensitivity limits defining the progressive increase in the pulse rate

3 EXPERIMENT

3.1 Method

3.1.1 *Human test subjects*

A total of six arbitrarily selected subjects (three females and three males) participated in the test. All subjects were young healthy individuals with a mean age of 23.17 years and standard deviation (SD) of 0.75 years. None of the subjects was an athlete, but all subjects were actively involved in sports activities. Ethical approval was granted for the study by Monash University, and all subjects completed written informed consent to participate in the experiment.

3.1.2 *Instrumentation for human movement measurement*

The IMSU was placed over clothing on the trunk of each subject in the L3 region of the lumbar spine for trunk tilt measurements. The unit was positioned to provide a 0° reading when each subject was standing in the tandem Romberg position prior to starting the experiment. Two VAs were used, one placed on each side of the trunk referring to the ML sway variations. Both the VAs and the IMSU were securely mounted using elastic body straps. Figure 4 depicts the device placements for the experiment.

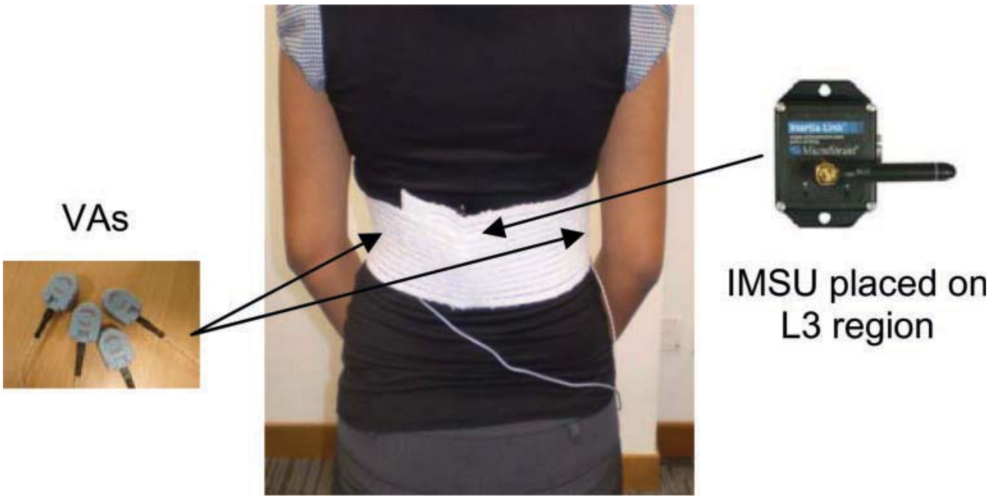


Fig. 4 Body-mounted instrumentation for postural control assessment during the tandem Romberg test

3.1.3 Experimental procedure

The tandem Romberg stance involved standing in one position with feet placed heel to toe (Fig. 5, extracted from reference [**29**]). For this study, trunk tilt while standing in the tandem Romberg stance was obtained to provide biofeedback based on ML sway variations.

Prior to the initiation of experiments, the subjects were provided with a brief familiarization period. During this time, each subject was introduced to the biofeedback system and each subject learned why a vibration cue was delivered and how to react to it. For this experiment, a boundary threshold range of ± 2° was utilized as the dead zone during which no biofeedback was active [**30**]. For biofeedback activation during boundary violations, Table 1 illustrates the vibration sensitivity control parameters utilized to indicate the extent of the violation.

Each subject was tested for the following four conditions during which they were instructed to maintain a good postural balance:

(a) ML postural balance, eyes open (EO) without real-time biofeedback;
(b) ML postural balance, EO with real-time biofeedback;
(c) ML postural balance, eyes closed (EC) without real-time biofeedback;
(d) ML postural balance, EC with real-time biofeedback.

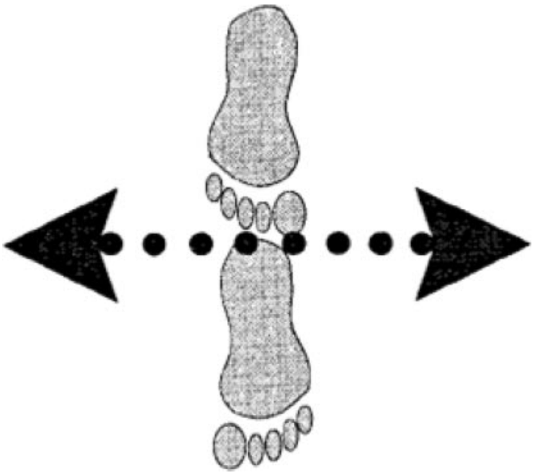


Fig. 5 The tandem Romberg stance

The training session was initiated with an audio indication at which the subjects started the test. Each subject performed the EO and EC tests for each condition over three trials, with each trial lasting 10 s. To reduce a learning effect occurring during the experiments, the test conditions were followed in the order of EO without feedback, EC without feedback, EO with feedback, and EC with feedback. Each subject was also given a short relaxation period of approximately 1 min at the end of each trial. The IMSU mounted on the trunk obtained the ML trunk tilt resulting during the test sessions at 100 Hz. VAs placed on the sides of the trunk indicated the variations in the trunk tilt during the training sessions to notify the subjects of their ML postural balance in correspondence to the target range.

3.1.4 Statistical analysis of sway measurements

Sway measurements were quantified by computing the r.m.s. of the ML trunk tilt. In order to quantify the usage of biofeedback during the tests, the instances at which biofeedback was activated over the complete duration of the tests were computed. To assess the significance of instantaneous biofeedback provided during the stability test, paired *t* tests were conducted for trunk tilt measurements for the two conditions EO and EC, confirming that the sway variations follow a normal distribution. Paired *t* tests were chosen for this evaluation because they permit low sample sizes and yield more statistical power, as each subject serves as his or her own control [**31**, **32**]. The threshold for statistical significance was set as 0.05.

3.2 Results

Figures 6(a) and (b) depict the trunk tilt measurements of a representative trial during each condition with and without biofeedback respectively. Reductions in variability and amplitude of trunk tilt are clearly displayed in the measurements plotted when biofeedback was in use.

For tests conducted with EO, the overall r.m.s. mean and SD obtained for trunk tilt were $0.78 \pm 0.24^\circ$ and $0.92 \pm 0.33^\circ$ with and without biofeedback respectively. The reduction in the trunk tilt during the EO condition, however, was not significant at $p < 0.05$

Table 1 Vibration sensitivity control parameters for biofeedback activation

Biofeedback activation range	Tilt angle control parameters	Vibration sensitivity/duty cycle (%)
Dead zone (no biofeedback)	$-2^\circ \leqslant \theta \leqslant 2^\circ$	0
Sensitivity level 1 (low vibration)	$2^\circ < \theta \leqslant 7^\circ$ (medial) $-2^\circ > \theta \geqslant -7^\circ$ (lateral)	20
Sensitivity level 2 (medium vibration)	$7^\circ < \theta \leqslant 12^\circ$ (medial) $-7^\circ > \theta \geqslant -12^\circ$ (lateral)	50
Sensitivity level 3 (high vibration)	$12^\circ < \theta$ (medial) $-12^\circ > \theta$ (lateral)	80

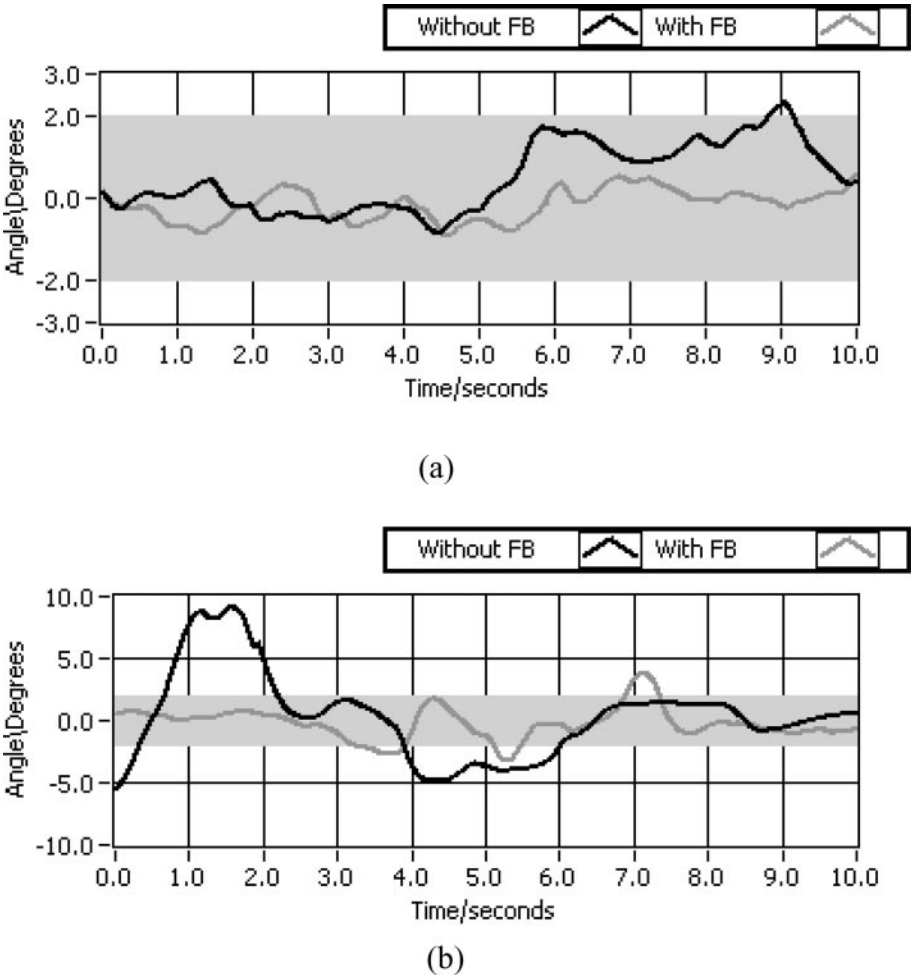


Fig. 6 The trunk tilt angle during (a) an EO trial and (b) an EC trial with and without biofeedback (FB)

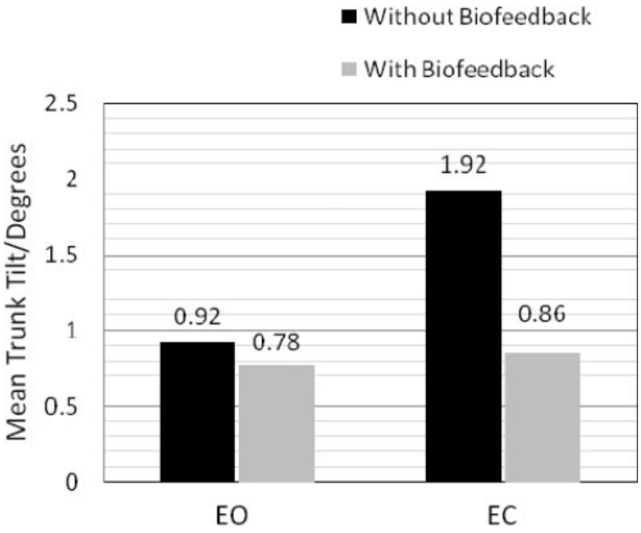


Fig. 7 Mean r.m.s. θ computed across all participants during the EO and EC trials in both conditions

with the addition of biofeedback. The mean of the instances at which biofeedback was activated during the EO tests over the full duration was 6.04 per cent, indicating that, although not significant, biofeedback has contributed to the reduction in the trunk tilt during the EO tests in comparison with no feedback. A 15.2 per cent reduction in the ML trunk tilt resulted with the inclusion of biofeedback.

For the EC tests, the overall r.m.s. mean and SD were $0.86 \pm 0.23°$ and $1.92 \pm 0.88°$ with and without biofeedback respectively. Conversely to the EO condition, the reductions in the trunk tilt obtained during the EC tests were significant at $p < 0.05$ ($p = 0.01$) with a mean biofeedback usage of 22.05 per cent throughout the tests. A 55.2 per cent increase in ML postural control resulted with the inclusion of biofeedback during the EC tests.

Figure 7 illustrates the overall mean trunk tilt across all subjects computed for the two conditions with and without biofeedback respectively.

3.3 Discussion

The objective of this study was to evaluate the biofeedback prototype for instantaneous assistive feedback using the tandem Romberg stability test. Trunk tilt was measured as the stability metric, as postural stability during standing can be estimated via trunk movements, which approximates the position of the body centre of mass [**33**]. With the use of the biofeedback prototype, reductions in the ML trunk tilt during standing in the tandem Romberg position in both the EO and the EC conditions were obtained. ML sway variations obtained with biofeedback during the EO test were smaller than those with no feedback. This observation is predictable as all participants were young healthy individuals with a good ability to maintain well-balanced postural control. However, usage of an average of 6.04 per cent biofeedback signalling over the trials implies that, although not statistically significant, feedback has influenced the reduction in the trunk tilt resulting during the EO tests. It can be hypothesized that, if tested with subjects having lower-extremity injuries, or experimented with a tighter training goal, or with a larger sample size, the influence of the biofeedback system during the EO tests would have been more evident. However, further experimentation is required to confirm or reject this hypothesis.

Tests conducted with EC were more challenging as the visual input to maintaining balance is removed [**14**, **27**] and the tandem Romberg position reduces the ML base of support. Hence, an increase in the trunk tilt movement was reported and the use of the biofeedback system during the EC tests was significantly demonstrated from the results. In comparison with no feedback, the r.m.s. trunk tilt was reduced when tested with the biofeedback system, showing a ML trunk tilt reduction of more than 50 per cent while receiving biofeedback of an average of 22.05 per cent over the trials. With the more demanding test challenge, the contribution of biofeedback and the improvement in trunk tilt were significantly exemplified from the results.

The experiment clearly demonstrates the effect of instantaneous biofeedback to maintaining ML trunk tilt when compared with no biofeedback. Reductions in the r.m.s. trunk tilt suggest that participants were able to use and interpret the information provided from the biofeedback system to decrease their ML sway variations. None of the subjects had any difficulty in learning the nature of feedback; they were easily accustomed to the wearable devices and the information provided by them. No subject reported any discomfort during the tests and all participants were able to continue the experiments in due course. Although placing the VAs over clothing may have slightly affected the strength of vibrations produced, all subjects indicated that the vibration stimulus was clearly perceivable.

With regard to the experiment conducted, the newly built prototype was verified and validated with the design specifications and requirements of a real-time biofeedback system. This included the size and weight of system devices pertaining to convenience in wearability, choice of biofeedback, removing the limitations that are commonly encountered in audio and visual feedback systems and wireless control, increasing portability, ease of use, and enabling remote monitoring. The development is novel in terms of its customizability in the hardware–software co-design, allowing designers and researchers to include add-on modules with different application programming interfaces for various human subject natures and tasks. The real-time software tools embedded enable system hardware reconfigurations, graphical and video visualization of movements monitored in real time, reconfigurations of biofeedback control parameters, visual feedback while generating vibrotactile signalling, storage of subject information, and post-training data analysis. The applicability of the system and the impact of immediate biofeedback through vibration stimulation were clearly demonstrated from the experimental results. Furthermore, results provided by the prototype could be used for long-term stability assessments, comparing balance measurements of injured subjects against healthy athletes, and for determining suitable balance training programmes based on stability evaluations. Hence, the application of the developed prototype for assistive feedback during stability assessments and balance training programmes involved in sports and rehabilitation could be foreseen. However, vastly varied dynamic movement experiments are needed to assess the viability of the system for providing real-time assistive feedback during dynamic conditions.

4 CONCLUSION

In summary, a biofeedback system with real-time functionality was developed and tested to provide assistive feedback during the tandem Romberg stability test. The system structure is a biofeedback control system with a wireless sensor known as IMSU, fully fledged integrated system software with the capability of including add-on tools for future developments, and a wearable wireless vibration stimulus unit for vibrotactile biofeedback. Devices integrated in the real-time embedded system developed were suitable for use as a feedback system in terms of physical characteristics, performance, portability, and remote connectivity and with possible system reconfigurations including any third-party embedded software modules. Two conditions were tested, EO and EC, and the efficacy of biofeedback was evaluated on the basis of trunk tilt variations obtained with and without biofeedback. The results indicate that information conveyed via vibration stimulus related to trunk tilt contributed to improving the stability maintenance. The testing carried out provides evidence that the current development is beneficial for sports training and rehabilitation programmes as a means for conveying instantaneous assistive feedback for performance improvement and injury prevention.

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APPENDIX

Notation

EC	eyes closed
EO	eyes open
IMSU	inertial measurement sensor unit
LB	lower bound
ML	medial–lateral
MS SQL	Microsoft Structured Query Language
RF	radio frequency
R1	vibration sensitivity level 1
R2	vibration sensitivity level 2
R3	vibration sensitivity level 3
SD	standard deviation
UB	upper bound
VA	vibrotactile actuator
θ	trunk tilt angle