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Abstract. Various leg exercises have been recommended to prevent deep vein thrombosis (DVT), a condition where a blood clot forms in the deep veins, especially during long-haul flights. Accessing the benefit of each of these exercises in avoiding the DVT, which can be fatal, is important in the context of suggesting the correct and the most beneficial exercises. Present work aims at demonstrating the fiber Bragg grating (FBG)–based sensing methodology for measuring surface strains generated on the skin of the calf muscle to evaluate the suggested airline exercises to avoid DVT. As the dataset in the experiment involves multiple subjects performing these exercises, an inertial measurement unit has been used to validate the repetitiveness of each of the exercises. The surface strain on the calf muscle obtained using the FBG sensor, which is a measure of the calf muscle deformation, has been compared against the variation of blood velocity in the femoral vein of the thigh measured using a commercial electronic-phased array color Doppler ultrasound system. Apart from analyzing the effectiveness of suggested exercises, a new exercise which is more effective in terms of strain generated to avoid DVT is proposed and evaluated. [DOI: 10.1117/1.JBO.18.9.097007]

Keywords: biomechanics; Bragg gratings; exercise evaluation; fiber optic sensing applications; fiber sensing; strain sensors.

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1 Background

Immobility of body or body parts due to surgery, pregnancy, illness, or long distance travel may subject one to the risk of deep vein thrombosis (DVT).[1] DVT is a condition where the blood clot forms in the deep veins of the body, typically in the legs.[2] The correlation between venous thromboembolism and air travel was established as early as 1954,[3,4] and the occurrence of DVT in long distance air traveling passengers has increased since then.[5]

The magnitude of DVT risk in long distance air travel has been difficult to resolve due to the lack of adequate data. From observational studies, it is estimated that 1 out of 500 individuals above the age of 50 years who fly for 12 h can develop symptomatic DVT.[6] A recent report has suggested that the risk increases by about 18% for each 2-h prolongation of travel duration.[7]

In legs, the arteries rely on the heart to force blood through them and the veins work against the gravity to transport blood with muscle contraction and relaxation to avoid DVT. Therefore, assisting blood circulation in the lower limb can reduce the risk of DVT especially during long hour flights. Several methods have been reported so far to increase venous circulation for DVT prophylaxis. Instrumental help has also been sought toward avoiding DVT, inducing small neuromuscular electrical impulses, which gently stimulate the common peroneal nerve behind the knee to activate the calf muscle pumps of the lower leg that return blood toward the heart.[8,9] However, this method is better suited for elderly people struggling to walk or people with impaired locomotion. The easiest way to activate the calf muscle pump activity or to increase blood velocity in the veins is to manually exercise the calf muscles by performing certain exercises.[10] Accordingly, most airline authorities recommend various leg exercises as a DVT preventative measure.[11–13] Nonetheless, several studies conducted with the support of various sensor technologies suggest that not all exercises recommended by airline authorities induce active contraction of the calf muscle and therefore may not be beneficial to the passengers in prevention of DVT.[14–17] In this context, the evaluation of the exercises suggested to avoid DVT using newer sensor methodologies is important.

In the present work, fiber Bragg grating (FBG) sensors have been employed to evaluate the benefit of the set of airline exercises suggested to avoid DVT. This is a follow-up of the previously reported work on measuring surface strain on the calf muscle while performing exercises using FBG sensors.[18] To validate the results obtained in the present study, the surface strain on the calf muscle, measured using FBG sensors during various exercises, has been compared against the blood velocity variation in the femoral vein of the leg obtained from a commercial color Doppler ultrasound (CDU) system.

Various inherent advantages of FBG sensors—such as nonrequirement of energizing voltage, high special resolution, multiplexing capability, high strain resolution, sweat/humidity resistance, ability to be woven into a fabric to take the ergonomic shape of the body, etc.—make them suitable for biomechanical applications compared to other types of sensors,

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specifically in measurement of surface strain for evaluation of physical exercises.

2 FBG Sensors and Instrumentation

FBG sensors have seen a considerable rise in the recent times, in their utilization in many varied applications.[19–21] As mentioned earlier, the present work employs FBG sensors as the sensing element for dynamic measurement of strain on the surface of the calf muscle while performing the exercises suggested to avoid DVT. As the volunteered subjects might perform the exercises differently, an IMU which measures accelerations and rotational attributes has been used to confirm the accuracy/repetitiveness of exercises.[22]

Examining the blood velocity in the veins is a known technique for patients with chronic venous disease.[23] Therefore, a commercially available CDU system is used on the femoral vein of the leg to measure change in blood velocity while performing exercises and the data obtained is compared against the results of the FBG sensors.[24–26]

3 Sensing Methodology

A 125-μm diameter, germania-doped, photosensitive, silica fiber has been used in the fabrication of FBG sensors of 3-mm gauge length, using the phase mask technique.[20] The sensors are surface bonded on the medial belly of the right gastrocnemius muscle, using a skin friendly silicon-based adhesive as the bonding agent. The position and the placement of the FBG sensor have been optimized in consultation with the physician present during the test. The IMU is also strapped on the calf muscle using a Velcro strap. The probe of the CDU is placed against the femoral vein of the thigh to find the variation in the blood velocity during the performance of the exercises.

The FBG sensor data is obtained in the form of change in the wavelength of reflected light from the FBG sensor, which is

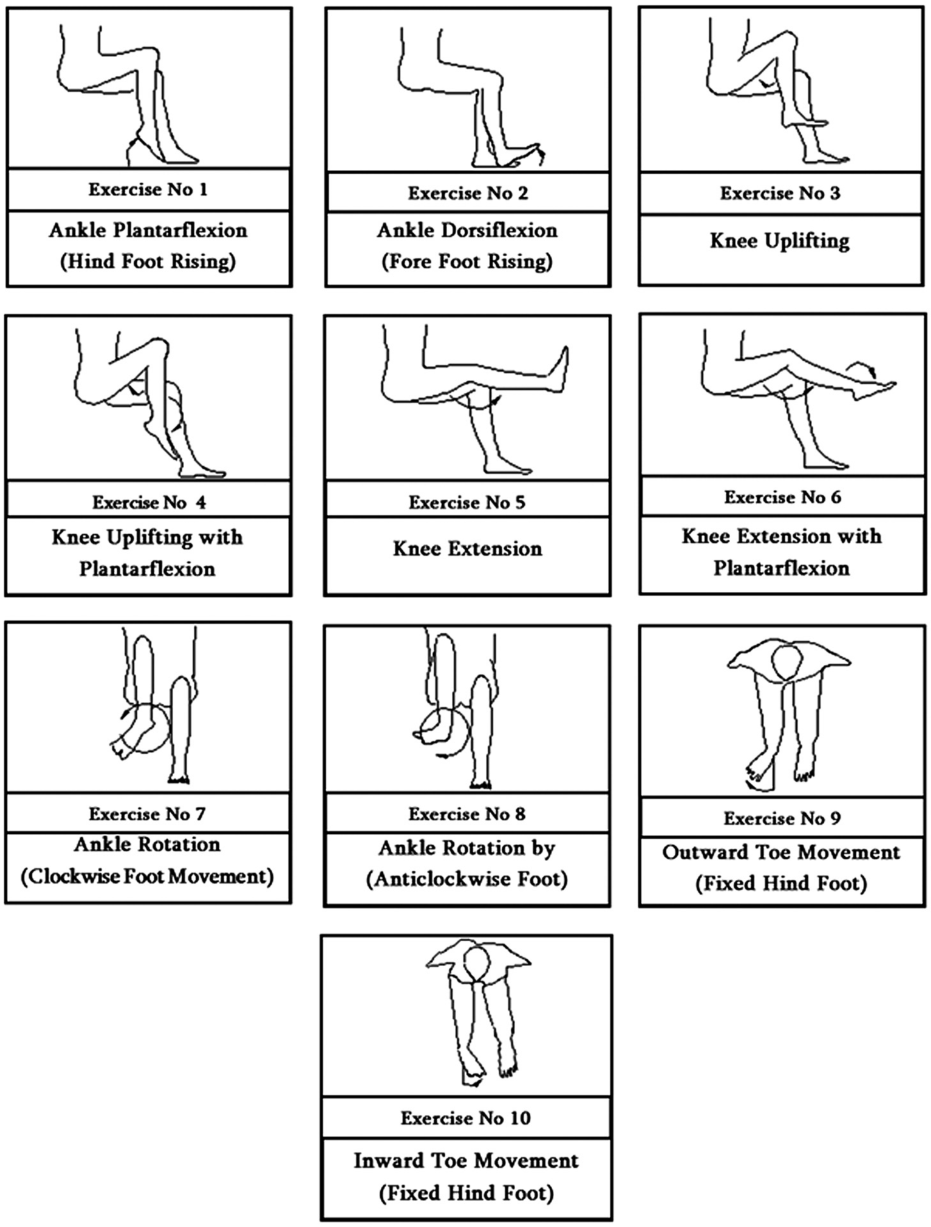

Fig. 1 Suggested exercises for avoiding deep vein thrombosis (DVT) considered for evaluation.

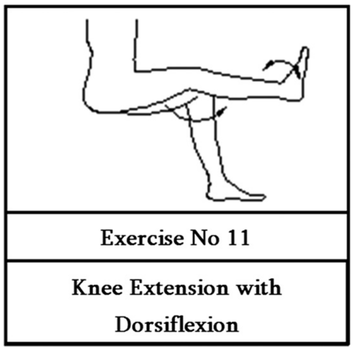

Fig. 2 The newly proposed exercise for avoiding DVT.

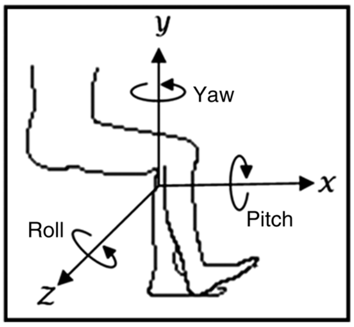

Fig. 3 The axes system used for inertial measurement unit (IMU) measurements.

further converted into respective strain on the surface in which the sensor was mounted.[27]

In the present study, the experiments are conducted in a controlled environment in the laboratory. The atmospheric temperature remains fairly constant over the entire time of experimentation. The FBG sensor is attached to all the subjects at least 10 min before the actual data is recorded. This provides ample time for the FBG to attain thermal equilibrium with the body temperature of the subject, avoiding possible errors due to temperature drift.

Data from all the three different sensing systems has been recorded simultaneously during the performance of the exercises by the subject. The data obtained from the IMU is used to find the accuracy of the repetition of the exercises performed by individual subjects with which an accuracy table is generated for all the exercises performed by each of the subjects.

Each exercise is repeated for five times by all the subjects, and the corresponding strain data has been recorded using a FBG interrogation system from Micron Optics (SM 130–700), at a sampling rate of 1 kHz.[28] The nature of strain generated (compression or tension) on the surface of the calf muscle depends on the movement pattern of the leg involved during each exercise. Irrespective of the nature of the strain generated on the calf muscle, whether it is tensile (positive strain) or compressive (negative), only magnitudes of strains are indicated for the purpose of illustration.

4 Experimental Details

A detailed experimental procedure has been devised in the present work to illustrate the usefulness of FBG sensors for monitoring strain on the calf muscle. Figure 1 shows all the exercises considered for evaluation in the present study involving lower leg movements suggested by many of the airline authorities and biomechanical experts.[11–13]

4.1 *Subjects*

Twelve healthy subjects (six females and six males) have volunteered for the present work. They are aged between 24 and 28 years and are of varying body mass index (BMI mean: 25). Before starting the experiment, required ethical procedures have been followed. The subjects have been examined by a general medical practitioner one day prior to the experiment. All of them have been declared to be in good health condition to participate in the experiment.

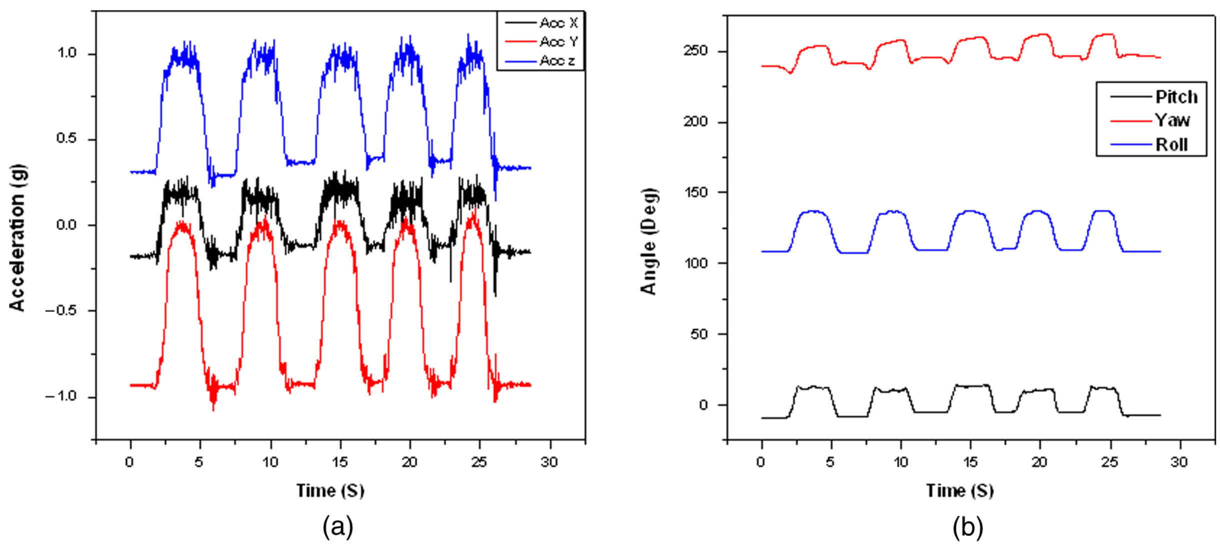

Fig. 4 IMU data for exercise 1 with repetition of five trials for validation of accuracy. (a) Accelerations of exercise 1 and (b) rotational attributes of exercise 1.

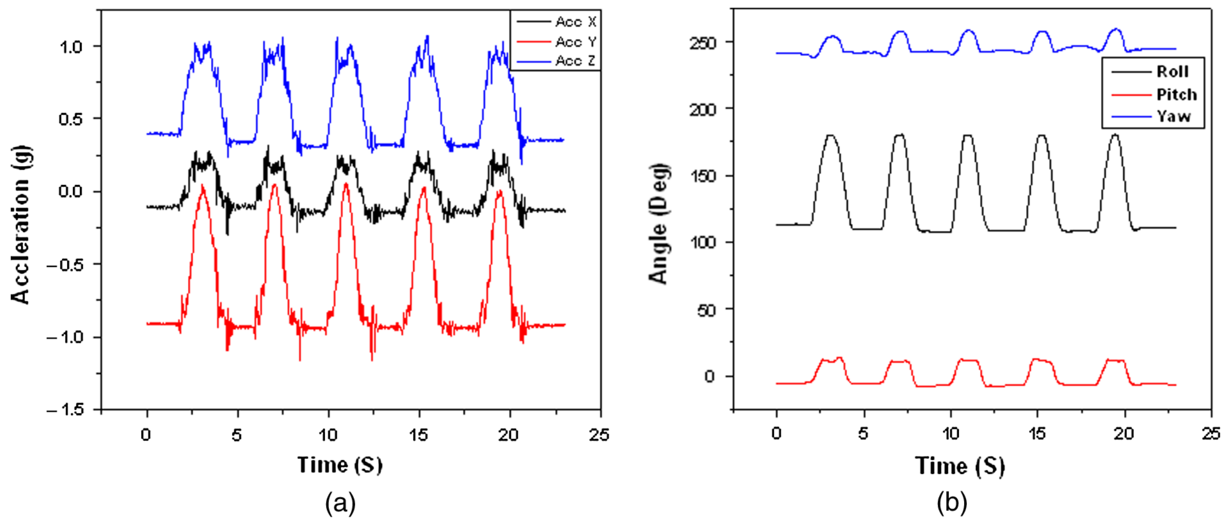

Fig. 5 IMU data for exercise 7 with repetition of five trials for validation of accuracy. (a) Accelerations of exercise 7 and (b) rotational attributes of exercise 7.

4.2 *Procedure*

The subjects are first briefed about the details of the experiment, such as the exercises to be performed, the posture in which it has to be performed, and the number of repetitions of each exercise. They are also instructed to repeat the exercises to the maximum extent of accuracy. To avoid fatigue error due to over straining the muscles of the subject, an interval of 5 min is given between two consecutive exercises.

4.3 *Proposed Exercise*

The work by O'Donovan et al.[14] has found that only few of the suggested exercises are beneficial in avoiding DVT. Since one of the authors associated with this work is an expert in yoga science, a new exercise has been proposed and evaluated. Figure 2 shows the proposed exercise in the present work, which involves extension of the knee with dorsiflexion of the ankle. The proposed exercise has also been evaluated for its performance in the same procedure adopted in the present work and the results were compared with the previously suggested exercises.

Table 1 Accuracy table generated for all the exercises from inertial measurement unit (IMU) data.

Exercise number	Accuracy (%)
1	95
2	94
3	93
4	92
5	92
6	93
7	86
8	85
9	95
10	93
11	95

5 Results and Discussion

As mentioned previously, data from all the three different sensing instruments has been recorded simultaneously during the performance of the exercise by the subjects.

5.1 *IMU Data Processing for Accuracy Evaluation of Exercises*

The axes system of IMU (mounted on the calf muscle) has been shown in Fig. 3. All the measurements are made with respect to the IMU's fixed axes system which outputs accelerations in X, Y, Z axes and rotational attributes like pitch, yaw, and roll. As the IMU with a flat surface has been strapped on a curved calf

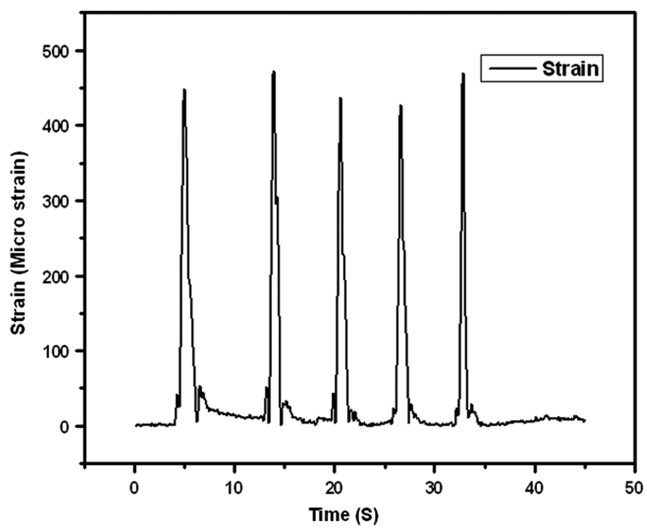

Fig. 6 Real-time strain generated during an exercise recorded by the fiber Bragg grating (FBG) sensor on the calf muscle.

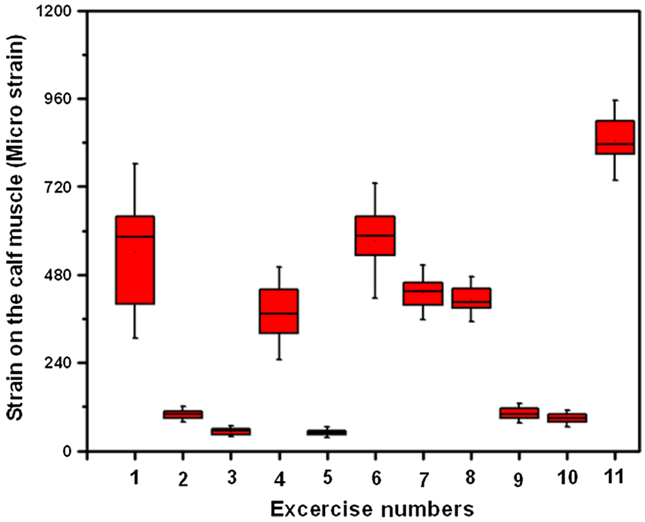

Fig. 7 Strain generated on the calf muscle during different exercises.

muscle surface, initial offsets in the readings of the IMU are expected in the obtained data and normalized. IMU measurements of two exercises (exercise 1 and exercise 7) performed by a typical subject are presented for illustration in this section.

Figure 4(a) shows the acceleration data along the three axes for five repetitions of the exercise, whereas Fig. 4(b) shows the angular rotational data acquired by the gyroscope in the IMU about the three axes. Similarly, accelerations and rotational attributes of exercise 7 are shown in Figs. 5(a) and 5(b), respectively.

From Figs. 4 and 5, it is evident that the subjects have performed the exercises quite accurately. Similar trends have been observed for all other exercises across all the subjects. The mean and standard deviation have been obtained for of all the six parameters (three axes and three rotational attributes). An average value of the standard deviation obtained for all the six parameters of each exercise is calculated and an accuracy table is generated, which is shown in Table 1. It can be seen

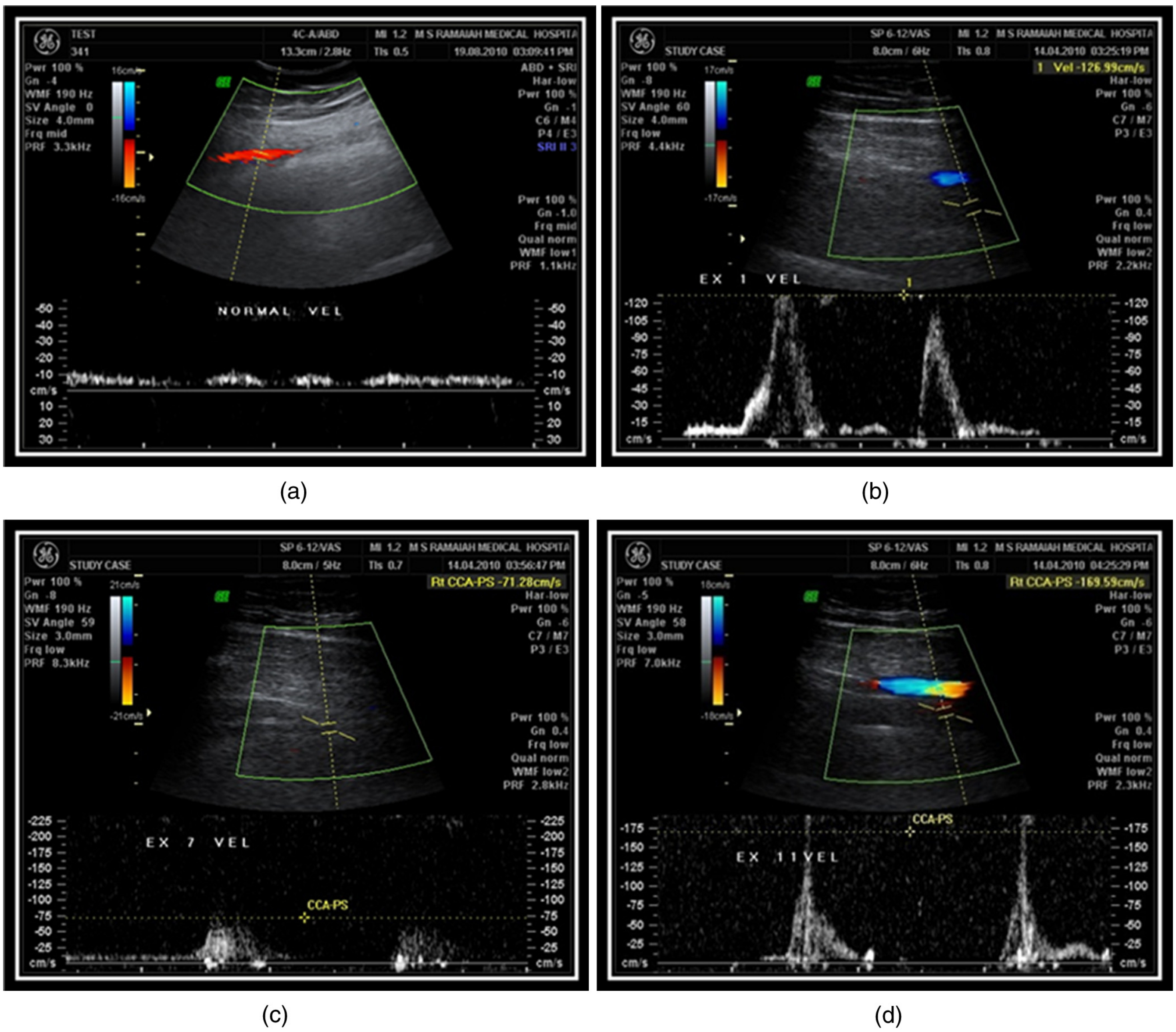

Fig. 8 Color Doppler ultrasound (CDU) results showing velocity of blood: (a) blood velocity during normal leg position, (b) blood velocity during exercise 1, (c) blood velocity during exercise 7, and (d) blood velocity during exercise 11.

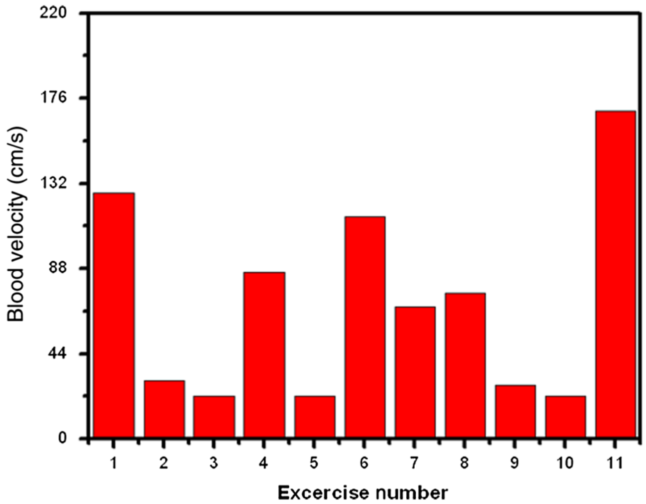

Fig. 9 CDU results showing peak blood velocities generated during different exercises.

from Table 1 that the accuracy levels obtained are in the acceptable range as the trials involved exercises from human beings.

5.2 *FBG Sensor Results*

Figure 6 shows the real-time response of FBG sensor on the surface of the calf muscle for a typical exercise exerting tensile strain. Five distinct and sharp peaks corresponding to five repetitions of the exercise can be observed from the plot. Peak strain values recorded by all the five trials are comparable, signifying the consistency of the exercise performed by the subject.

Figure 7 shows the box plot comparing each exercise for all subjects with mean, median, percentile ranges and spread of the strain on the calf muscle, with respect to time. From Fig. 7, it can be seen that among all the 11 exercises evaluated (including the newly suggested exercise), three distinctive groups of exercises evolve in terms of strains generated; group 1 comprises exercises 1 and 6, reading an average strain of 550 $\mu\varepsilon$ that are found to be exerting more strain on the surface of the calf muscle compared to the rest of the suggested exercises. The second set (group 2) comprises exercises 4, 7, and 8, reading an average strain of 400 $\mu\varepsilon$ on the surface of the calf muscle. Group 3 contains the rest of the exercises, namely exercises 2, 3, 5, 9, and 10 which exert comparatively minimal strain values in the range of 100 $\mu\varepsilon$ on the surface of the calf muscle. Among all the evaluated exercises in this work, the newly suggested exercise, exercise 11 stands out best, exerting a mean strain of 925 $\mu\varepsilon$ which is about 25% greater than the highest strain generated exercise (exercise 1) among the evaluated suggested airline exercises.

5.3 *Study with CDU System*

Figure 8 shows CDU scans measuring the blood velocity in the femoral vein for a sample subject at a normal upright position and while performing typical exercises. Figure 8(a) shows the CDU scan illustrating blood velocity in the femoral vein when the subject is sitting in the normal upright position prior to performing any exercise. From Fig. 8(a), it can be seen that the velocity of blood is about 10 m/s. Figures 8(b)–8(d) show the blood velocity in the vein during exercises 1, 7, and 11, respectively, for two repetitions. It can be seen from Fig. 8 that the peak blood flow velocities for exercises 1, 7, and 11 are 126.99, 71.28, and 169.59 cm/s, respectively. Similar scans have been obtained for all the other suggested exercises shown in Fig. 1.

Figure 9 shows the plot between the blood velocity variations with respect to different exercises performed by the subject. It can be seen from this Fig. 9 that exercises 1 and 6 (group 1) are relatively more effective in terms of the variation in the blood velocity measured in the femoral vein. From the obtained CDU scans, exercises 4, 7, and 8 can be considered as group 2, which have shown intermediate magnitudes of variation in the blood velocity. On the same lines, the rest of the exercises, namely exercises 2, 3, 5, 9, and 10, comparatively show minimal variation in blood velocity as shown in Fig. 9. It is interesting to note that a similar grouping of exercises has also been obtained from the surface strain results of FBG sensor instrumentation (Fig. 7). A tabulation of the strain generated and the variation in blood velocity for all the exercises are shown in Table 2, which also depicts the groups evolved from both the FBG sensor and CDU techniques.

Envelope comparison of Fig. 7 against Fig. 9 and from the exercise grouping obtained, confirming that the results of FBG sensors and the CDU system follow the same trend, match well with the work reported by O'Donovan et al.,[14] confirming that the proposed FBG sensor methodology is reliable and accurate, thereby substantiating the potential of the FBG sensors in evaluating the suggested exercises.

It can also be seen from Fig. 7 that the newly suggested exercise (exercise 11) generates more strain on the calf muscle and similarly more velocity in the femoral vein of the thigh (Fig. 9), proving its effectiveness in avoiding DVT compared to any of the previously suggested exercises; Exercise 11 proposed in this work records the strain and velocity which is 25% higher in terms of strain and blood velocity than exercise 1 which has recorded maximum among the suggested set of exercises (exercises 1 to 10).

6 Conclusion

A new methodology using FBG sensors has been demonstrated to sense the strain on the surface of the calf muscle and to evaluate the benefit of the exercises suggested to avoid DVT during long distance flights. The results from the FBG sensors have

Table 2 Comparison of results from both fiber Bragg grating (FBG) sensor and color Doppler ultrasound (CDU) system for all the exercises.

Compared techniques	Parameter measured	Position of measurement	Group 1 exercises	Group 2 exercises	Group 3 exercises	Best exercise
FBG sensor	Surface strain ($\mu\varepsilon$)	Skin of calf muscle	1,6	4,7,8	2,3,5,9,10	11
CDU	Blood velocity (cm/s)	Femoral vein	1,6	4,7,8	2,3,5,9,10	11

been compared against the medically proven CDU system. In addition, an IMU has been used to measure the accuracy of repetition of each of the exercises performed by the volunteered subjects to ensure the reliability of the results obtained. Further, a new exercise has been proposed which is more effective as indicated by more strain on calf muscles and larger blood velocity in femoral vein.

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