วารสาร
เทคนิคการแพทย์และกายภาพบำบัด
JOURNAL OF MEDICAL TECHNOLOGY AND PHYSICAL THERAPY

นิพนธ์ต้นฉบับ
ORIGINAL ARTICLE

A novel experimental analysis for the scientific study and evaluation of sprained ankle

N. Nasseri, F. Almasganj, S. Najarian *, S. H. Farkoush

Abstract

Ankle sprains are the most common among athletic injuries and are responsible for great time lost in athletes' practices. However, the scientific study and evaluation of this injury, in professional athletes, has received less attention. This paper presents a novel experimental analysis to scientifically study the status of athletes who suffer from ankle sprain and also to make a scientific comparison between athletes who suffer from ankle sprain, and normal cases. This evaluation can ultimately help physicians determine the best time for those cases who suffer from ankle sprain to restart their activities. In this study, three normal cases and three volunteers with a sprained ankle (sex: M, age = 17 $\pm$ 5 yr, height = 1.85 $\pm$ 0.05 m, body mass = 85 $\pm$ 10 kg, foot length = 244-245 mm) who all of them gave consent to be tested, have participated in a designated test. Four features (whole force on each foot during its mid-stance phase, mid-stance phase duration, swing phase duration, and supination torque) have been selected and extracted. Results have shown that, the first three features are essential in studying the status of athletes with sprained ankle and can be beneficial in evaluating the status of sprained ankle cases during healing process.

Keywords: Ankle sprain, Recovery time, Foot pressure

Faculty of Biomedical Engineering, Amirkabir University of Technology, Tehran, Iran
*Corresponding author: Professor Siamak Najarian, Biomedical Engineering Department, Amirkabir University of Technology, 424 Hafez avenue Tehran Iran. Tel: +98(21)64542378; Fax: +98(21)66468186;
e-mail: najarian@aut.ac.ir.

Introduction

The scientific study and evaluation of the status of athletes after injury, is among the biggest challenges in sports medicine practice. The importance of this study and evaluation is to help decide when an athlete has sufficiently recovered from an injury and can return to his/her sport[1-3]. This issue is important because quite often the physician is under pressure from various sources to return the athlete back to play quickly after injury. But if an athlete returns to play before an injury has adequately healed, there is a risk of re-injury, which could add significantly to the time already lost from the sport. Besides, a worse possibility is the occurrence of a new injury due to compensation for a previously unhealed injury.

Ankle sprains are among the most common sporting injuries [4-10].This injury is common among athletes in running and jumping sports as well as basketball players, and is responsible for great time lost in their practice [11]. Besides, early assessment of sprained ankle is very important because it can limit the rest time for injured people especially for an injured athlete who wants to decrease time lost in practice [12-14]. Moreover, continuous evaluation of the status of sprained ankle can help the physician to determine the proper time for the athlete to restart his/her sport activities. The high number of professional athletes suffering from ankle sprain related to their sport activities and the importance of this injury in their professional life call for an in-depth scientific evaluation of the status of these cases after injury.

This paper presents a novel experimental analysis which can be used to make a comparison between athletes who suffer from ankle sprain and normal cases. This evaluation can ultimately help to determine the best time for those cases who suffer from ankle sprain to restart their activities. Previously, evaluation of plantar pressure distribution, during gait in athletes with Functional Instability (FI) of the ankle joint was performed to address the hypothesis that the gait characteristics differs between normal subject and athletes suffering from FI of the ankle joint [7]. Many researchers study plantar pressure distribution in patients with diabetic neuropathy [15]. Su, Xu, and Yi-Ning have proposed a novel gait analysis system based on adaptive neuro-fuzzy inference system [16]. Liu, Inoue, and Shibata have developed a wearable sensor system for quantitative gait analysis [17]. Artificial neural network is highly efficient and it was used for gait recognition [18].

Gait impairment is a significant problem in cases with sprained ankle, leading to decreased activity and limitations in function [19]. Besides, walking, requiring high coordination of the neural systems and muscles, is a complex activity [16]. This complexity can be reflected in foot pressure patterns during walking. Acquiring and processing this large numbers of complicated data needs a computerized analysis system to be done in a short time.

In this paper, we present a novel experimental analysis which evaluates foot pressure due to gait impairment in cases with sprained ankle. This system is capable of extracting useful features and information, from a large number of original gait data, quickly and gives reliable results. Results can compare data from an athlete with sprained ankle and a normal case and ultimately can lead to clarifying health status of the athlete with sprained ankle. Ankle sprains are the most common of all athletic injuries and occur when the ankle is turned unexpectedly in any direction that is further than the ligaments are able to tolerate [8-9]. Most sprains occur during sports which involve jumping and side to side movement like basketball, volleyball, and soccer [11,21]. More often than not, athletes are the ones who always experience ankle sprains. Since they often utilize their bodies and at some times prove to overtax their limits, this can result in sprained foot. Additionally, continuous jumping and running takes its toll upon the ankle and the muscles within [21]. Ankle sprains are classified in three different groups according to their severity. Sprains grade 1 are those with stretched and/or minor tear of the ligament without laxity. Grade 2 covers those sprains with tear of ligament plus some laxity. In grade 3 the patient faces complete tear of the affected ligament.

Nowadays, one of the most important problems in sports medicine practice is deciding when an athlete has sufficiently recovered from an injury and can return to sport. Doctors use different ways to evaluate the status of the athlete after the occurrence of ankle sprain. They may order X-rays, or move the ankle in various ways to see the status of the injured ligament. They may even order an MRI (magnetic resonance imaging) if they suspect a very severe injury to the ligament with no improvement [22]. X-ray and MRI are relatively expensive, and X-ray has additional radiation exposure problems that may impose potential health risks. Palpation also has various disadvantages. It is subjective and experience dependent. The gait analysis method proposed in this paper, can give objective and reliable results. The details will be explained in the following sections.

Materials and methods

Materials

A fifty-nine pressure sensor (59PS) system was used to provide necessary pressure data which were essential for the evaluation of foot pressure in the cases with sprained ankle. The system was a simple and low-cost device and was designed specifically for evaluating ankle sprains. This system had the ability to provide essential information for ankle sprain evaluation and to eliminate unnecessary information.

The insole was flexible and its thickness was 0.35 mm. This system, with its Round-shaped FSRs (Force Sensing Resistors) which were 8.0 mm in diameter, had been used as foot-pressure monitoring system in previous studies [8,20].

Figure 1 (a) and (b) shows size and structure of the system and pressure sensors. As it is obvious in Figure 1 (a), the insole is in the size of a normal foot (24.7cm long, 8cm wide in forepart and 10.9cm wide in back part).

The system includes an interface circuit for transmitting data to computer. The interface circuit consists of four analog multiplexers. These analog multiplexers can be used to transfer the data from 64 pressure sensors to the microprocessor. In this study, 59 input ports of the interface circuit are used, though. The interface circuit's dimensions are 9 cm by 5 cm and by 7 cm (height). The pressure sensors' output, which was collected by a micro-processor unit, converts to a 10-bit digital signal (0−1,023), at a selected frequency of 100 Hz. The collected data were transmitted through a serial connection to a computer. Data can be saved in '.txt' format, in the computer after transmission. Sensor array was scanned to get pressure data and then process response value of the sensors every time.

System specification

The system has already been calibrated and **Figure 2** (a) shows the calibration system. The calibration diagram is also shown in Figure 2 (b).

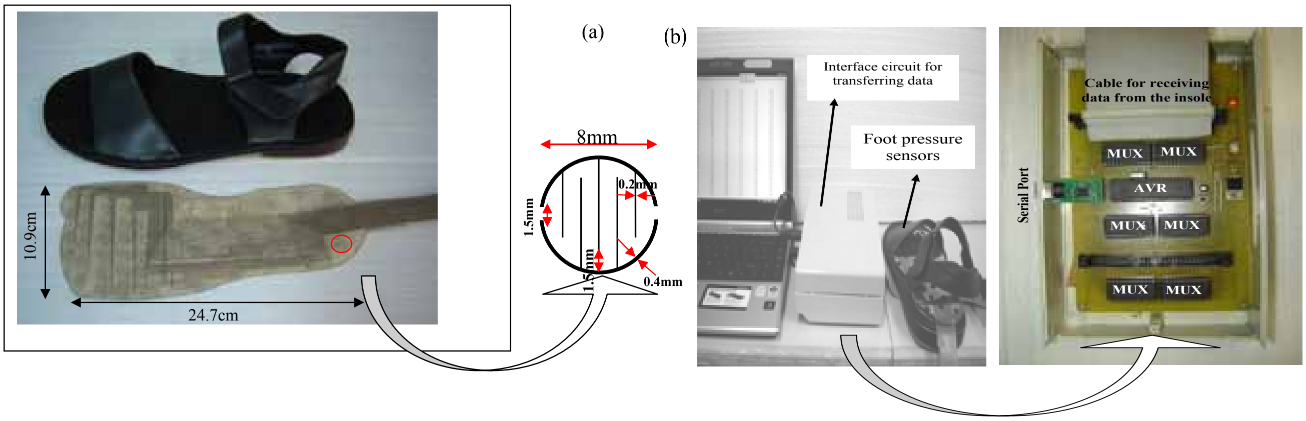

Figure 1 (a) Size and structure of designed system and pressure sensors. (b) Final fabricated system.

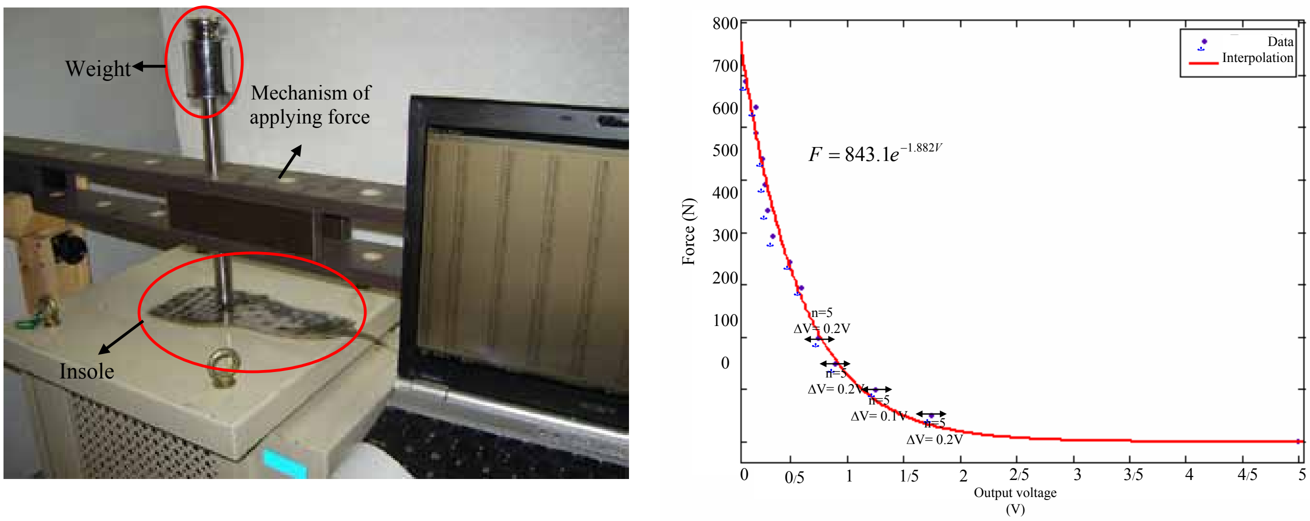

Figure 2 (a) Calibration system. (b) Calibration diagram.

The saturation limit for the sensors used in this study is obtained as 784 N. Besides, the resolution of the sensors is measured as 1 N and the dead band as 0.8 N. To examine the accuracy of the sensors' output, the output was double-checked by tension testing system (Zwick/Roell) as it is shown in figure 3 and minimum accuracy of 95 % was reported.

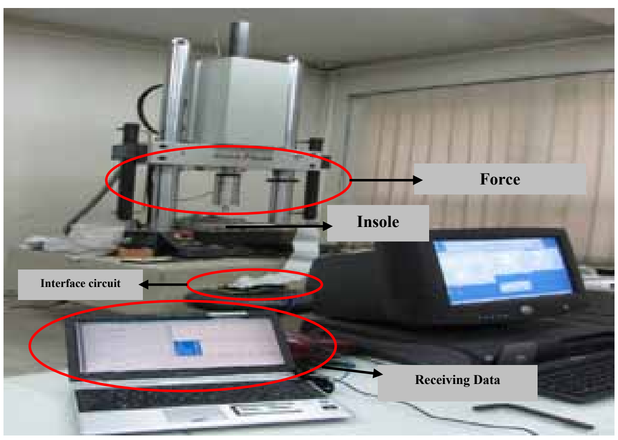

Figure 3 Testing the accuracy of the sensors' output by tension testing system (Zwick/Roell).

Clinical test

The experimental study was performed with six left-legged (dominant foot: the left one) male athletes (sex: M, age = 17 $\pm$ 5 yr, height = 1.85 $\pm$ 0.05 m, body mass = 85 $\pm$ 10 kg, foot length = 244-245 mm), who all gave consent to be tested. There were two groups of participants. The first group was the one that we refer to as control group. In the control group there were three participants that had no history of ankle sprain and they also had no other remarkable lower limb injury, which means that they had never been under treatment because of an injury in their lower limbs. The second group (test group) was also consisted of three participants with a sprain that had recently occurred to their left ankle. This means that they (i.e., those in the test group) participated in this test before they tried any kind of treatment. In this group, participants may have had some background in ankle sprain (in their left foot) but they have had neither other remarkable lower limbs injuries nor any history of sprain in their right foot. The type of the injury for the participants in this group has been assessed to be grade 2, according to the assessment of a professional chiropodist. In this group, the test was conducted between five to ten hours after the injury. To start the test, participants wore the sandals with pressure measurement insole in one of them and performed two trials of walking in a clinic. Participants were requested to precede ten steps in their natural cadence, in each trial.

Each athlete repeated the test a couple of times, and in each time, data collected from a different foot. The foot pressure system was used for measuring the plantar pressure at 59 positions covering the whole plantar area at 100Hz. Data collected during one minute and saved as a ".txt" file.

Segmentation and feature extraction

Feature extraction is a key step in most pattern analysis tasks. First step in feature extraction is segmenting the signal. The gait cycle can be divided into different phases and sub-phases, so that each action of the foot and leg can be evaluated at specific sequential time periods. The gait cycle of each leg is divided into the stance phase and the swing phase. The stance phase is the period of time during which the foot is in contact with the ground. The swing phase is the period of time in which the foot is off the ground and swinging forward. There are also several sub-phases. Among the sub-phases, mid-stance is used in this study. During mid-stance the other foot is in swing phase and so all the body weight is born on the stance limb alone. This means that mid-stance is a time when lower limb is particularly susceptible to injury. Mid- stance is also the longest phase of the stance period.

In this paper, segmentation has been done in a way that parts of gait signal which are relevant to mid-stance phase have been separated. In this way, sensor's outputs were detected as mid-stance phase when more than 80 % of pressure sensors were ON (under pressure). This kind of segmentation can make a large piece of useful information available.

A normal gait is symmetric. It means that gait patterns are similar in both feet in comparison with each other [23-25]. Monitoring gait of a person with sprained ankle, during healing period and determining the similarities between feet can help to find out the efficiency of healing process and the health status of the athlete. However, what comes to mind about athletes with sprained ankle is that, due to pain sensation in the sprained ankle foot, after the injury the athlete cannot distribute his mass equally between his feet. Besides, the athlete after injury is prevented from walking through his injured foot and prefers to exert minimum pressure on his injured ankle. Supination torque is another factor which is important in sprained ankle cases. Because ankle sprain may lead to ankle instability which puts the athlete in danger of recurrent sprains, supination torque may increase during mid-stance phase.

In the next step, to reduce the complexity of classifiers the most significant features should be selected and extracted. Features must be selected in a way that can clarify the differences between classes. According to information about the differences between a normal gait and gait in an athlete with sprained ankle, in this research work, we selected four features from gait signal. Selected features include: maximum force on each foot during the mid-stance phase, mid-stance phase duration, swing phase duration, and supination torque during mid-stance phase. Considering previous works, supination torque can easily be calculated through equation 1[8, 26].

$$SupT(N.m) = -2.068 + 0.0910x(P_{60}) + 1.318x(P_{72}) + 1.549x(P_{98}) + error \quad (1)$$

The three locations were approximately at the fourth/fifth metatarsalphalangeal joint (Position 60), the third metatarsalphalangeal joint (Position 72), and the second/third distal phalange (Position 98) as they are shown in **Figure 4**[26]. Besides, the overall root mean square error was obtained 6.91Nm, which was about 6% of the peak values recorded in the five sport motions (113Nm)[26].

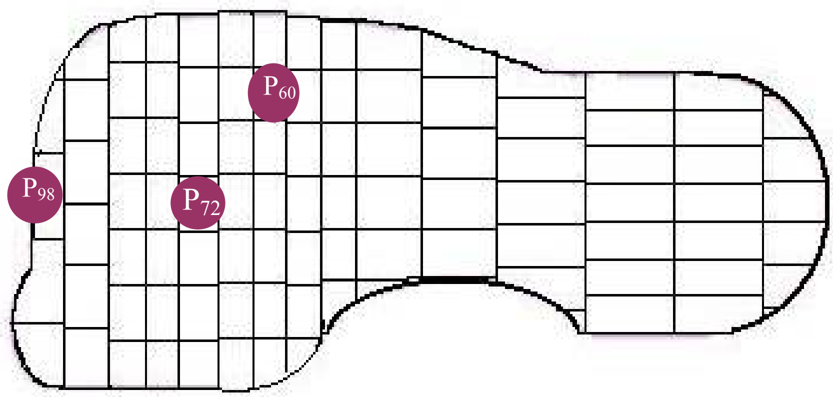

Figure 4 Three essential locations: fourth/fifth metatarsalphalangeal joint (Position 60), the third metatarsalphalangeal joint (Position 72), and the second/third distal phalange (Position 98), for calculating the supination torque according to equation 1.

Results

MATLAB (version 7) was used for changing ".txt" files to matrices, and also segmentation, and feature extraction. Eight features were extracted from each subject. Each four features in any subjects, was relevant to each foot. Comparison between control group and athletes with symptoms of ankle sprain has been made through bar diagrams.

Figure 5 shows the extracted features, from left foot and right foot of a participant, as a sample of sprained ankle group, with 90kg weight, 188cm height, and 245mm foot length. This participant (mentioned above) was a wrestler with symptoms of sprained ankle in his left foot. In all cases, sprained ankle diagnosis was made by an expert physician.

In all the figures below, bars which are relevant to mid-stance duration and swing duration are five hundred times and the bars relevant to supination torque are twenty times greater than their real magnitudes. **Figure 6** clarifies the differences between extracted features in three athletes with symptoms of ankle sprain.

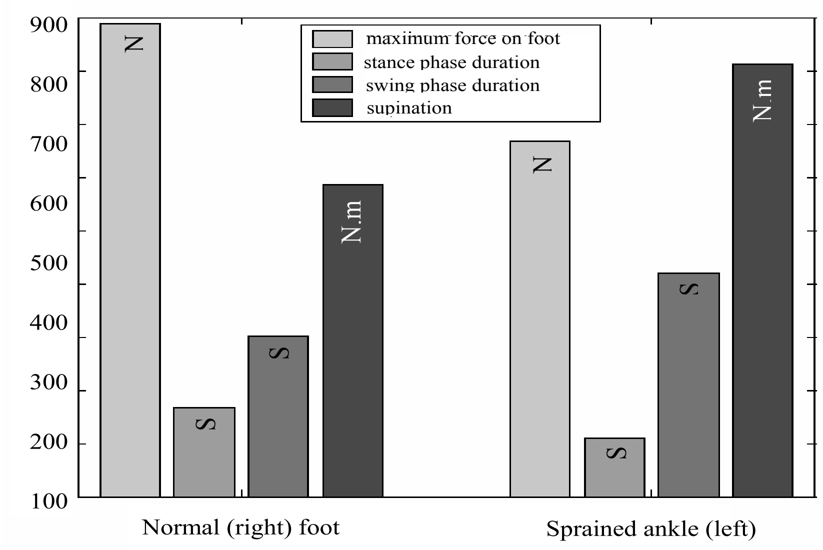

Figure 5 Feature comparison between normal and injured foot in an athlete with sprained ankle.

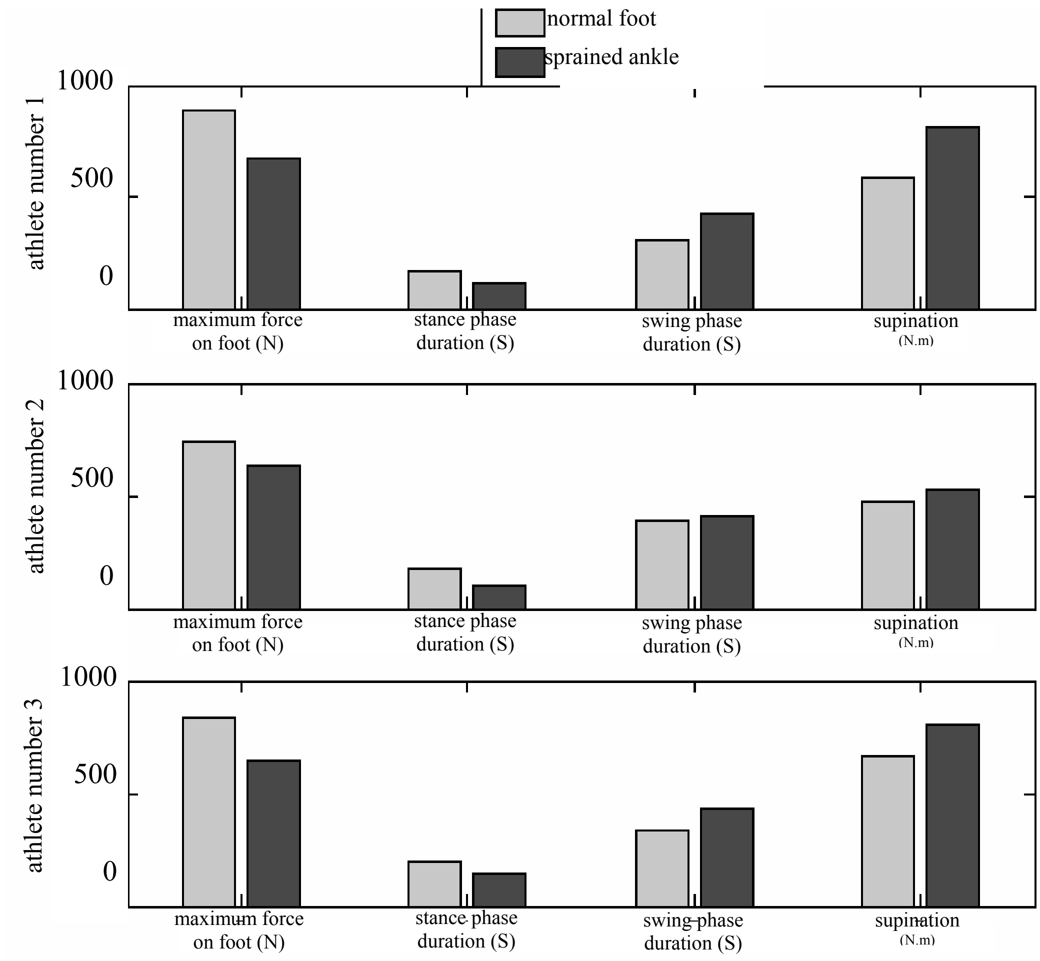

Figure 6 Differences in extracted features for each volunteer athlete.

In **Figure 7**, differences between extracted features in a sample normal case is obvious.

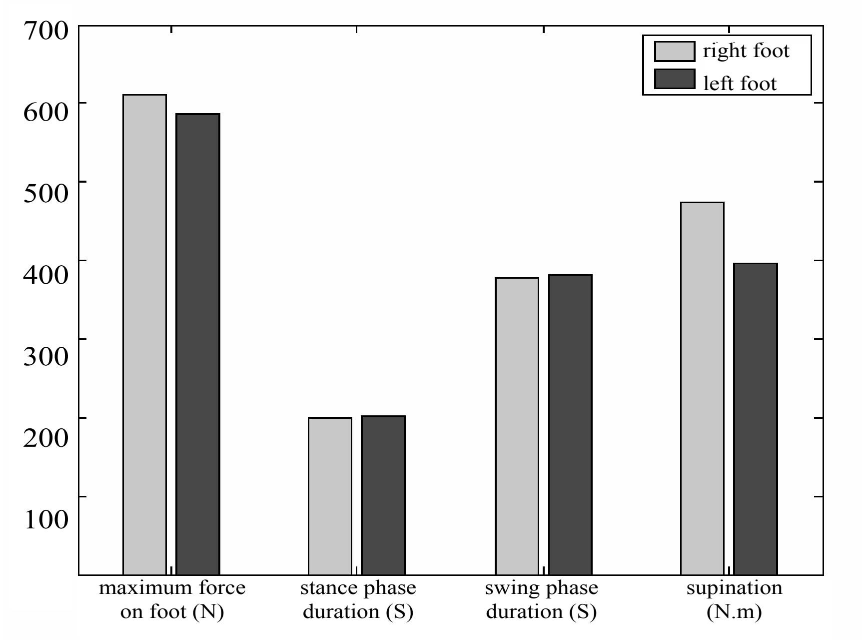

Figure 7 Feature comparison between feet of a volunteer normal athlete.

In order to show the differences between magnitudes of each feature in the group with a sprained ankle in comparison with the control group, the data from a participant with sprain ankle and a normal participant are provided (**Table 1** and **Table 2**).

Table 1. Magnitude of each feature in an athlete in the group with sprained ankle.

Type of foot	Whole Force (N)	Mid-stance Duration (s)	Swing Duration (s)	Supination (N.m)
Right Foot	888	0.3361	0.6037	29.3210
Left Foot (Sprained)	668	0.2193	0.8401	40.6462
Difference Between Two Feet%	-32.93%	-53.26%	28.14%	27.86%

Table 2 Magnitude of each feature in an athlete in the control group.

Type of foot	**Whole Force (N)**	**Mid-stance Duration (s)**	**Swing Duration (s)**	**Supination (N.m)**
Right Foot	611	0.3990	0.7556	23.6806
Left Foot	587	0.4041	0.7621	19.8212
Difference Between Two Feet%	-4.09%	1.26%	0.85%	-19.47%

Discussion

To our knowledge, this is the first reported system which is capable of extracting useful features from foot pressure signal, in order to evaluate the status of an athlete after ankle sprain. Four features have been extracted and significant differences were visible between control (normal athlete) group and the group with a sprained ankle. As Figures 5-6 show, significant differences in the magnitude of four extracted features are visible between the normal foot and sprained ankle foot in the group of athletes with a sprained ankle. Comparison between Figures 5-6 and Figure 7 which is relevant to a normal athlete in the control group determines that although the magnitude of the whole force on foot during mid-stance, mid-stance phase duration and swing phase duration are almost the same in feet of a normal case, significant differences are visible between the magnitude of these features between feet of a case with a sprained ankle. Figure 6 shows that during mid-stance phase, the amount of exerted force on each foot differs between feet of an athlete with sprained ankle although they are almost the same between feet of a normal case. Moreover, the mid-stance phase duration is different between feet of an athlete with sprained ankle, albeit mid-stance phase durations are the same in both feet of a normal athlete in the control group. The same explanation is true about the swing phase. Although the swing phase duration does not change severely between feet of a normal case, it differs significantly between feet of a case with sprained ankle. Figure 6 also shows an increased supination torque in sprained ankle in comparison with a normal foot in the same athlete. However, the same difference is obvious in a normal case in Figure 7. Therefore, the difference cannot be only because of sprained ankle. Other factors such as bad habits in walking can also cause this difference.

As it is obvious in Tables 1 and 2, in an athlete with a sprained ankle, the whole force on the sprained ankle, during its mid-stance phase, is apparently less than the whole force on the normal foot of the same athlete, during its mid-stance phase. It means that, due to ankle pain in the sprained ankle, the volunteer athlete with sprained ankle prevents himself from exerting his whole weight on the sprained ankle and prefers to distribute his weight between two feet when the sprained ankle is on the ground. Table 1 clarifies that the athlete has exerted only 75 % of his weight (Body mass: 90 kg) on his sprained ankle, during its mid-stance phase.

It is also obvious that, due to ankle pain in an injured volunteer athlete, the athlete prefers to minimize the time which his sprained ankle is on the ground and tries to move forward by maximizing swing phase in his abnormal ankle. Therefore, according to the data in Tables 1 and 2, mid-stance phase duration in sprained ankle has decreased 53.26 % and the swing phase duration has increased 28.14 %.

Table 1 also demonstrates that supination torque is larger in a sprained ankle in comparison with a normal foot. However, as it is obvious from Table 2 other factors are also responsible for increasing supination torque, such as bad walking habits, etc. Thus, increased supination torque may also happen in a normal case and it is not a significant feature in evaluating sprained ankles.

As it is discussed above, in this study we were able to distinguish a group of athletes with sprained ankle from those athletes who did not have a sprained ankle. Additionally, these results have been obtained by a few number of data from just 59 sensors which is incredibly less and more simple than previous studies.

Conclusion

A 59-PS system has been used to get essential data from different volunteers both in control group and in a group which includes athletes with sprained ankle. Three normal cases and three volunteers with a sprained ankle (sex: M, age = 17 $\pm$ 5 yr, height = 1.85 $\pm$ 0.05 m, body mass = 85 $\pm$ 10 kg, foot length = 244-245 mm) who all of them gave consent to be tested, have participated in the test. MATLAB (version 7) has been used to convert data that is saved in computer, to matrices and extract essential features from them.

Four features have been selected and extracted. Selected features include: whole force on each foot during its mid-stance phase, mid-stance phase duration, swing phase duration, and supination torque. Results have shown that, the first three features are essential in evaluating sprained ankle cases. Since in sprained ankle, exerted force on foot, and mid-stance phase duration is less and swing phase duration is more in comparison with a normal foot, monitoring these features during healing process can help the physician or the physiotherapist a great deal. These medical evaluations can facilitate the clinician's task in finding out when the foot pressure signal shows that the athlete has become close to his normal status and can go back to sport world.

Acknowledgements

Authors would like to express their gratitude to the Center of Excellence of Biomedical Engineering of Iran, based in Amirkabir University of Technology, Faculty of Biomedical Engineering, for its contribution.

References

1. O'Loughlin PF, Hodgkins CW, Kennedy JG. Ankle sprains and instability in dancers. Clin J Sport Med 2008; 27: 247-62.
2. Podlog L, Eklund RC. High-level athletes' perceptions of success in returning to sport following injury. J Sport Exerc Psychol 2009; 10: 535-44.
3. Stracciolini A, Meechan III WP, d'Hemecourt PA. Sports rehabilitation of the injured athlete. Clin Pediatr 2007; 8: 43-53.
4. Chen QC, Zhang WY, Youn U, Kim H, Lee I, Jung HJ, et al. Iridoid glycosides from gardeniae fructus for treatment of ankle sprain. Phytochemistry 2009; 70: 779-84.
5. Curtis AK, Laudner KG, McLoda TA. The role of shoe design in ankle sprain. J Athl Training 2008; 43: 230-3.
6. Lamb SE, Marsh JL, Hutton JL, Cooke MW. Mechanical supports for acute, sever ankle sprain: A pragmatic, multicentre, randomized controlled trial. The Lacent 2009; 373: 575-81.
7. Merolli A, Uccioli L. Plantar pressure distribution during gait in athletes with functional instability of the ankle joint: preliminary report. J Orthop Sci 2005; 10: 298-301.
8. Nasseri N, Almasganj F, Najarian S, Farkoush SH. An embedded insole, applicable in signal processing: sprained ankle assessment. IJIITA 2009; 2: 144-50.
9. Schemitt S, Melnyk M, Alt W, Gollhofer A. Novel approach for a precise determination of short-time intervals in ankle sprain experiments. J Biomech 2009; 42: 2823-5.
10. Willems T, Witvrouw E, Delbaere K, De Cock A, De Clercq D. Relationship between gait biomechanics and inversion sprains: a prospective study of risk factors. Gait Posture 2005; 21: 379-87.
11. Leanderson J, Wykman A, Eriksson E. Ankle sprain and postural sway in basketball players. Knee Surg Sport Tr A 1993; 1: 203-5.
12. Aminian K, Robert Ph, Buchser EE, Rutschmann B, Hayoz D, Depairon M. Physical activity monitoring based on accelerometry: validation and comparison with video observation. Med Biol Eng Comput 1999; 37: 304-8.

13. Coutts AJ, Slattery KM, Wallace LK. Practical test for monitoring performance, fatigue and recovery in triathletes. J Sci Med Sport 2007; 10: 372-81.
14. Martin B. Ankle sprain complication: MRI evaluation. Clin Podiatr Med Surg 2008; 25: 203-47.
15. Cavanagh PR, Ulbercht JS. Clinical plantar pressure measurement in diabetes: rationale and methodology. The Foot 1994; 4: 123-35.
16. Su X, Xu Z, Yi-Ning S. A novel gait analysis system based on adaptive neuro-fuzzy inference system. Expert Syst Appl 2010; 37:1265-9.
17. Liu T, Inoue Y, Shibata K. Development of a wearable sensor system for quantitative gait analysis. Measurement 2009; 42: 978-88.
18. Rahati S, Moravejian R, Kazemi FM, editors. Gait recognition using wavelet transform. Proceeding of the 5th International Conference on Information Technology; 2008 April 7-9; New Generations, NV. Las Vegas; 2008.
19. Brown C, Paudua D, Marshall SW, Guskiewicz K. Individuals with mechanical ankle instability exhibit different motion patterns than those with functional ankle instability and ankle sprain copers. Clin Biomech 2008; 23: 822-31.
20. Najarian S, Dargahi J, Mehrizi AA. Artificial tactile sensing in biomedical engineering. New York: McGraw-Hill; 2009.
21. Oztekin HH, Boya H, Ozcan O, Zeren B, Pinar P. Foot and ankle injuries and time lost from play in professional soccer players. The Foot 2009; 19: 22-8.
22. Wessely MA. MR imaging of the ankle and foot: a review of the normal imaging appearance with an illustration of common disorders. Clin Chiropractic 2007; 10: 101-11.
23. Bauckhage C, Tsotsos JK, Bunn FE. Automatic detection of abnormal gait. Image Vis Comput 2009; 27: 108-15.
24. Muniz AMS, Nadal J. Application of principal component analysis in vertical ground reaction force to discriminate normal and abnormal gait. Gait Posture 2009; 29: 31-5.
25. Schutte LM, Narayanan U, Stout JL, Selber P, Gage JR, Schwartz MH. An index for quantifying deviations from normal gait. Gait Posture 2000; 11: 25-31.
26. Fong DT, Chan Y, Hong Y, Yung S, Fung K, Chan K. A three-pressure-sensor (3PS) system for monitoring ankle supination torque during sport motions. J Biomech 2008; 41: 2562-6.