XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6–11, 2009, Lisbon, Portugal

WIRELESS INSOLE SENSOR SYSTEM FOR PLANTAR FORCE MEASUREMENTS DURING SPORT EVENTS

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Abstract −We are developing a wireless system that measures online the forces between foot and insole with a low-cost laminated capacitive sensor matrix. This measurement system can be utilized to monitor the timing and movements of the legs of an athlete during throwing, jumping and running in various sports events. The measured data is intended to be used to improve coaching. We chose the javelin throw event as a case study for our sensor system. We measured the force signals under both feet during several throws. Analysis showed that the measured signals provide additional information for coaching.

Keywords insole sensor, sports, force measurement

1. INTRODUCTION

We are testing embedded insole sensors in order to measure timing and force data online during sports events. In this paper, we focus on the javelin throw as a case study but the measurement concept can be utilized in other sports as well. We tested our insole sensor system in this application to get knowledge how the system works in real environment and to find out if the preliminary measurement data has enough information in order to make coaching more efficient. We cooperate with a professional coach to interpret measured signals. The aim of this project is to make the insole sensor a part of a larger ambient sensor network which can be used as a coaching tool to determinate how the athlete performed the exercise. Other sensors in this system can be for example video cameras, accelerometers and biopotential measurements like EMG. These sensors will be placed in the garments and elsewhere in the environment around the athlete.

The main users of the planned measurement system are the coaches and athletes of the events like javelin, long jump and sprint. One research question is what is the best user interface and how the measured data should be illustrated. In an optimal situation, an athlete would get easy-to-understand feedback immediately after the exercise event. In javelin application, the complex multichannel signals should be processed to easily interpretable form. We will try to find out whether the characteristics of the measured signals can be used to describe if the throw was performed correctly. We will focus on studying what information we are able to extract from the block leg during the actual throw moment.

In sport applications, the plantar forces have been measured with insole sensor systems and force sensitive plates or platforms. Both of these methods have their drawbacks. The problem of the force platforms is that they can only measure a few steps because of the limited area of the platform. In the case of the javelin throw event, for example, a thrower has difficulty in aiming the block leg at a platform. The challenges with the insole sensor systems are the metrological characteristics of the measurement systems and the ambiguity of the signals.

The measurement of the forces between foot and shoe with a wireless flexible insole sensor system still has challenges. The insole sensors systems have many known problems like mechanical durability, stability during long-term use [1,2], nonlinearity, hysteresis and the need to adjust offsets and sensitivity. More problems arise when the insole sensors are placed in a shoe. In most of cases the surface in the shoe is not totally flat and this may change the offset values of the sensors, and when the shoe is worn, the foot compresses the insole. This makes the interpreting of the force signals ambiguous. Moving toes in the shoe, for example, create a signal even if the shoe is held in the air because it changes the initial compression situation. These challenges have to be taken into consideration when the measurement signals are interpreted.

The insole sensor system that we are using was originally designed for a rehabilitation application [3-5]. The idea is to measure the forces between foot and insole with a low-cost laminated capacitive sensor matrix and embedded read-out electronics. In comparison to other existing in-shoe measurement systems like the F-Scan® systems [6,7] and the Pedar® systems [8,9], we are trying to make more application-oriented devices that can be easily integrated to larger ambient measurement network. At the moment, our insoles have less measurement channels than commercial insole systems, but we can easily alter the place and the shape of these sensors depending on the application. We also have simple custom-made read-out electronics and wireless link. In the future, this helps us to integrate the insole sensor system to other body area measurements. The custom-made electronics and software also give an interesting case study to develop wearable networks and methods to integrate electronics to garments.

2. METHODS

We have designed and manufactured a custom-made pair of capacitive insole sensors that fit into the track shoes or spikes of an athlete. This measurement system was tested during two separate training sessions. During the first session we used two insole sensors (in this case the left leg is called the block or support leg) to record signals from both feet simultaneously. Events like walking, running and javelin throws were recorded. Events were also filmed with a video camera. The collected data was combined and the value of the data was evaluated in cooperation with a professional coach in order to design suitable data evaluation methods and a user interface for javelin application. In the latter training session, we tested the block leg insole in order to evaluate the repeatability of the measurements.

2.1. Capacitive insoles

The concept of this measurement system is to use a laminated low-cost capacitive insole sensor matrix to measure localized forces on the sole. The forces make the capacitive elements in the insole to compress and this can be detected as a change in the capacitance value. Manufacturing of an insole is straightforward; all layers are cut to correct shape and then laminated to a stack. The capacitive sensor elements of the insole are formed when a 5 mm thick EPDM rubber sheet and conductive fabric layers are laminated over the electrode pattern and wirings on a flexible PCB. A more detailed description is in reference 3. We can alter the place, size and shape of the capacitive elements just by changing one patterned layer. This gives us an easy way to specify the insoles for different applications. The tested custom-made insoles measure the force between foot and insole in five areas as illustrated in Fig 1. The design of the right foot insole is a mirror image of the left insole. There are two capacitive sensor elements under the heel, two under the ball of the foot and one in the area of great toe. The multiple elements under the heel and the ball of the foot are used to sense if the foot is in balance. The weight of the insole is 35 g.

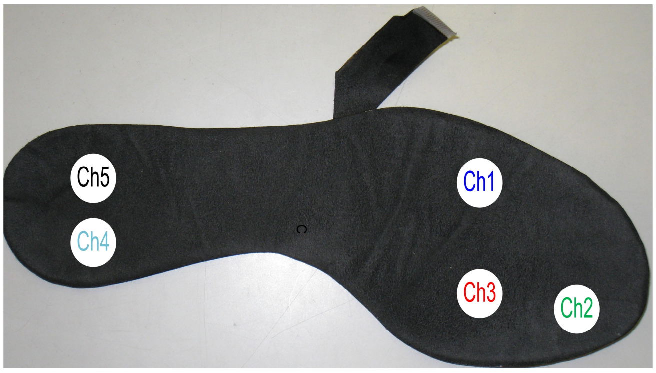

Fig. 1. The insoles used in our measurements were custom-made to fit the track shoes. There are five measurement areas in the insole. The place and the size of the capacitive sensor elements inside the insole are illustrated with white colour.

2.2. Measurement system

The insoles were attached to a wearable measurement system in order to enable synchronized sampling and data transfer. The wearable measurement system consists of two insoles, two measurement nodes, a Zigbee-compliant radio and a digital wired network (four wires). We chose to test a wired body area network in combination with one radio instead of a fully wireless system in this case because we did not want to place batteries in each node.

The custom-made sensor nodes were used to read the capacitance values of the capacitive sensor elements in the insoles. A node contains a capacitance-to-digital converter (AD7142, Analog Devices) and an ATmega168 microcontroller which is used to handle the converter-IC and the communication to an outside network. The weight of the node with a plastic casing is 17 g (actual node board weighs 6 g). The nodes were attached to the track shoes with a Velcro tape just above metatarsus. At this point, the nodes are connected to each other and to a Zigbee-compliant radio (105 g with 3 AAA batteries) with a wired body area network. The radio is fixed to waist. The wired network is used to synchronize the sampling. The sample frequency of the measurement is 100 Hz. The radio of the body area network forwards measurement data to the PC. In the latter training session, only one measurement node was used. We wanted to measure as realistic data as we could and the non-elastic wired network slightly hindered the athlete. We also adjusted the range of the capacitive read-out electronics to better fit this application which includes high force impacts. This was done by attenuating the stimulus signal of the capacitance-to-digital converter.

2.3. Signal processing

The capacitance-to-digital converters in the measurement nodes give 16-bit digital values representing the capacitances of the sensor elements. The converter has an option to compensate the offset capacitances. By using this option, hardware related offset values were compensated when the system was taken in use. However, when the insole is worn, the foot will compress the elements and alter the offset values. The case-specific offset values were detected from data and removed. In this case of the block leg, we used the readings taken just before the step in the release phase as offset values. The offset values of the right leg were taken at the moment when the leg is in the air. In order to compare multiple throws, the data has to be synchronized. With the javelin throw data, we choose to use the moment when the block leg hits to ground as a reference. This event is relatively easy to detect from data.

2.4. Development of the user interface

In order to use this measurement system as a tool for the coaching, we need a user interface, which provides the information on the multichannel force signals in easily interpretable form. In sports applications, a reliable device, which can measure multiple specific quantities has very little use in coaching unless signals can be tied to concepts which are familiar in the field of sports. This requires a lot of event-specific knowledge. In order to ease the interpreting of the signals we linked the data of one practice throw to a video signal. The interface used to illustrate the data is show in Fig. 2. This combined data was evaluated in cooperation with a professional coach. With this procedure, we tried to get new ideas how to make an interface which processes the multichannel signals and provides the essential information. This interface is planned to give feedback to an athlete after the sport event.

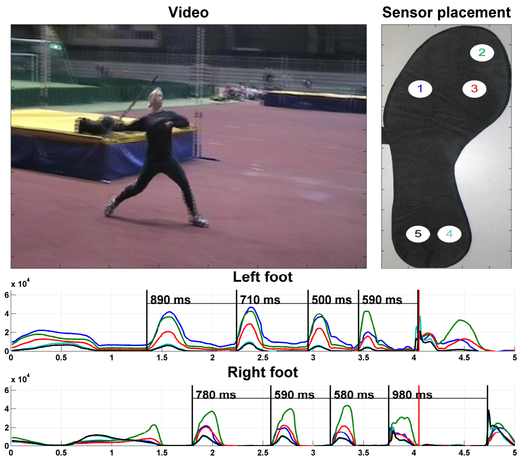

Fig. 2. User interface ties the recorded multichannel force data to a video sample in order to make interpreting signals easier.

3. RESULTS

At the first measurement session, signals of both legs were recorded during multiple training throws. The signals of the block leg insole during one example training throw event are presented in Fig. 3. The respective signals of the right leg are shown in Fig. 4. In the beginning of the data, the athlete takes one slow step in place (0-1.5 s). Next, the athlete runs forward and takes 4 steps with the block leg (1.5-4 s). On the fifth step of the block leg the athlete throws the javelin. At the end of the data, the athlete lands the right leg to the ground. There is an observable compression at the sensors number 1, 2 and 3 (the ball of the foot and great toe) in the block leg insole even when the leg is in the air. This results from the position of the ankle during the cross-stepping phase. In the signal of the right leg, it can be noticed that the athlete uses her great toe as a support for the steps.

One of the aspects of this research is to find out if the insole sensor is able to measure the plantar forces under the block leg when it is giving support to the athlete during the release phase of the throw. The signals measured during this step are illustrated in Fig. 5. According to the measurements, this step has two phases. In the first phase, the heel hits the ground first and shortly after that the whole area of the foot gives support to the throw. The athlete releases the javelin during this phase. This phase lasts approximately 200 ms. In the second phase, the load of the body moves to the ball of the foot and the great toe.

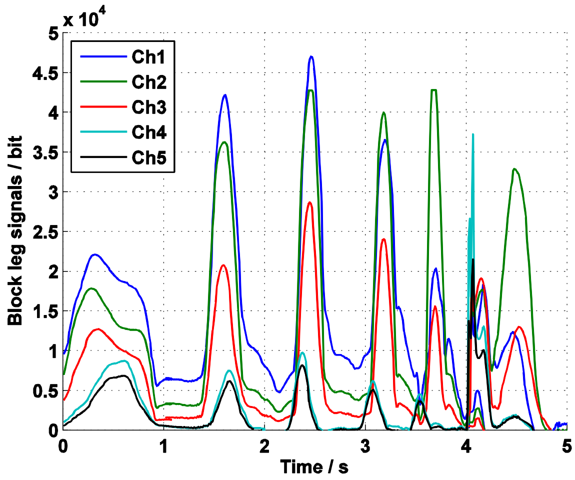

Fig. 3. The signals measured during one training throw under the block leg. See Fig. 1 for the placement of the sensors.

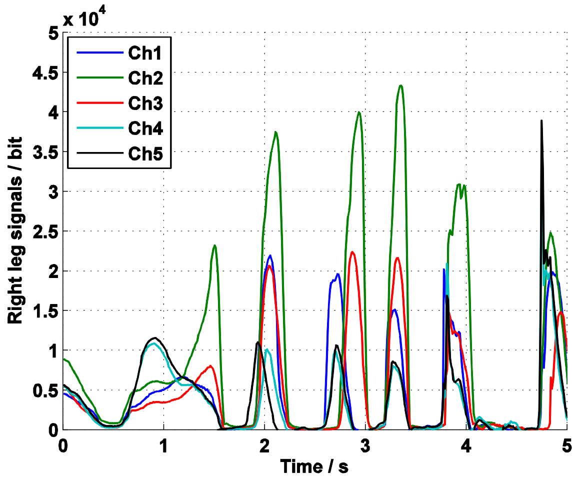

Fig. 4. The signals measured during one training throw under the right leg during the same throw as in Fig. 3.

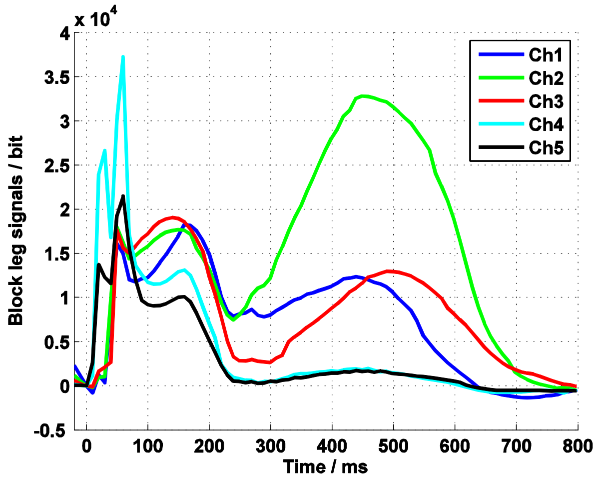

Fig. 5. The block leg signals during the release phase of the javelin throw event.

One use of the measurement system will be to monitor if there is difference in the supporting forces between throws. For this reason we asked the athlete to make three as similar throws as possible. The signals of channels 2 and 3 are shown in Fig. 6.

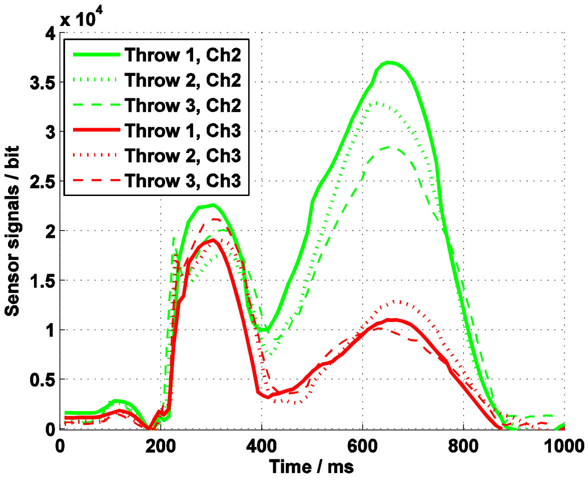

Fig. 6. An athlete tried to repeat similar throw three times. The signals of three separate throws are illustrated. The throws are synchronized at the moment where the block leg hits the ground.

In order to find out if the most critical timings of the throw can be estimated from the sensor data, the signals of the great toe and heel sensors (numbers 2 and 4) are illustrated during the support and release phases in Fig 7.

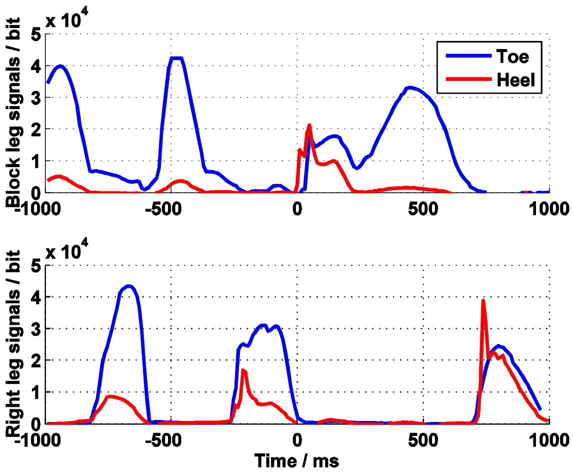

Fig. 7. The signals of heel and great toe sensors can be used to estimate the timings of the throw.

In the second measurements session, we asked the athlete to make six as similar regular throws as possible in order to evaluate the repeatability of our measurement system. The averages of the throws are shown in Fig. 8. The data of the channel 1 was lost because of a connector failure. The standard deviations of these measurements are shown in the Fig. 9.

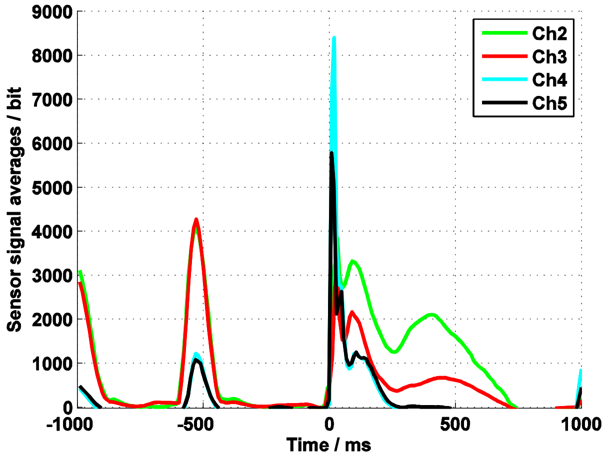

Fig. 8. An athlete repeated similar throw six times. The averages of the throws are illustrated.

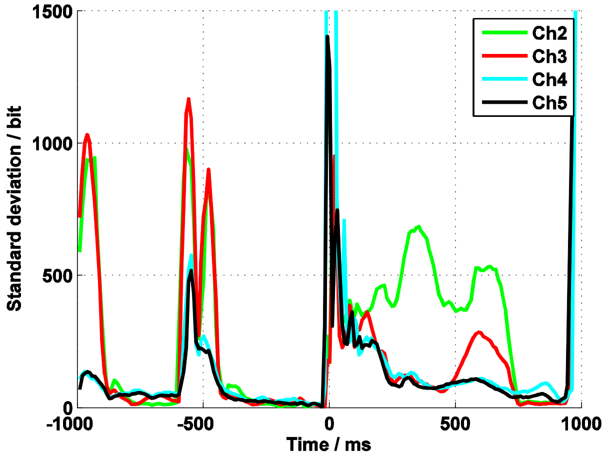

Fig. 9. The standard deviations of six similar throws.

By using this measurement system, we should be able to find out flaws in technique. As an example, we made a test where we compared the signal of channel 3 between the regular and warm-up throws (six throws of each type). The averages of the regular and warm-up throws are shown in Fig. 10. The two sigma limits of the regular throws are also shown. In case of warm-up throws, the time between steps is shorter. According to this data, there is more load on the sensor number 3 during some parts of the delivery phase in case of warm-up throws.

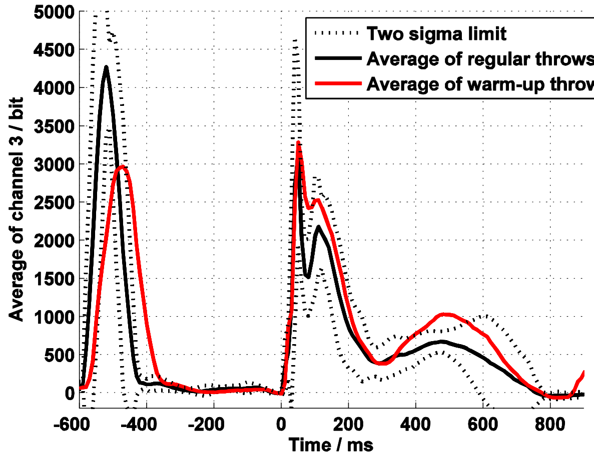

Fig. 10. The averages of the channel 3 differ between regular and warm-up throws.

4. DISCUSSION

At this stage of development, we show our measured signals as bit values representing force rather than the units of force or pressure. This is due to the lack of reliable means to calibrate individual sensors inside the track shoes. We also have to study how linear is the change of the capacitance values of the sensor elements compared with pressure. At this point, it is not totally clear if it is possible to get reliably quantitative values with this measurement method in this application because of the unwanted properties of the flexible capacitive insoles. However, in many sports applications, the repeatability of the measurements is more important than the exact force values from the coaching point of view.

According to the collected preliminary data and field testing, the use of the insole sensor system in the javelin throw applications and sports in general seems promising. However, field testing showed that, in sport applications, a wired network between shoes might be simple solution but because of large movements it is unpractical. In the future, the wired network has to be replaced with a wireless link or synchronized data loggers. The mechanical durability of the system has to be improved because the electronics, cables and connectors are prone to physical damage. The physical protection of the measurement system is crucial in sports applications.

As the signals in Fig. 3 indicate, the removal of the offset values of the capacitive sensors is problematic. The initial differences between channels originate from the physical asymmetry of the wiring in the insole and can be removed. Unfortunately, when the shoe is worn, the foot compresses the insole which alters the offset values. In javelin application, the removal of the offset values is even more complicated because of the rotated position of the ankle of the block leg during the cross-stepping phase of the throw. This changes the initial compression in the shoe and thus affects the reading of the sensors. According to the measurement data, the values of the sensors 1, 2 and 3 change just before the actual throw because the athlete turns the block leg pointing forward again. Similar changes in the initial compression situation and the bending of the insole in the shoe makes the interpreting of the signals ambiguous in some cases. However, in some degree this applies to all flexible insole sensor systems that are worn inside of a shoe.

The results shown in Fig. 5 indicate that our measurement system may suite to monitoring the plantar forces during the release phase of the javelin throw event although some details of the system need improvement. As shown in Fig. 5, when the sole hits the ground, the signals of the insole sensor, especially under the heel area, are changing fast thus making the signal jagged. This indicates that the sample rate of the measurement is too low.

As the results in Fig. 6 show, the insole sensor is able to capture the behaviour of the force distribution during the release phase of the throw. The throws indented to be similar do not seem to differ much. The synchronization of the signals just before the impact of the final step seems to enable the comparison of the forces under the block leg. If this procedure is automated, curves similar to Fig. 6 can be shown to coaches in order to compare throws.

One research question is if there is a way to obtain a sufficient estimate for the total force under the foot of the block leg during the final step of the throw. The preliminary test measurements indicate that it might be possible to obtain an estimate by adding up the weighted force readings of the channels and scaling this value. This requires that the sensor elements have adequate linearity and there is a method of removing the offsets of the channels in the similar way each time. The higher sampling rate would also make the estimate for the total force more accurate because the step during the throw is fast and only about 20 samples are now recorded. However, by using the existing read-out electronics, the sample rate can be raised only by reducing the number of channels. Eventually, a compromise has to be made between the accuracy and the sampling rate because of the limitations of the wireless link. If a correlation between the exit velocity of the javelin and the forces under the block leg is studied, it has to be taken into account, that this type of sensor only measures forces normal to insole. It might turn out that the shear forces have to be measured as well in order to get a comprehensive view of the forces under the block leg.

In the javelin throw application, the timing of the steps in general and the timing of the support and release phases has great importance. The pace of the steps should increase towards the end of the throw event. In order to get the total picture of the event, the synchronized signals of both legs should be observed. According to the results given in Fig. 7, the timing of the steps of the right leg can be reliable estimated from data. In the case of the block leg, it is more difficult to sort out when the leg is in the air and when it is on the ground. This is due to the additional alternating compression on the sensor 1.

According to the results in Fig. 8 and Fig. 9, if the same throw event is repeated, similar signals are recorded from the channels 3, 4 and 5 every time. However, the signal under the great toe seems to vary. This might be a feature of the technique, not a fault of the measurement system. It can be also noticed that the synchronization inaccuracy and the low sampling frequency increase the standard deviation if there is fast impacts in the signal. With this data set, it is impossible to conclude which is the cause of the variation between thows, the measurement system or the athlete.

If this insole sensor is used as a tool to indicate the flaws in technique, we have to compare a measured result with some existing model. In order to create a model for a good throw, an average and two sigma limits of six regular throws were calculated. When comparing the averages of the warm-up throws and the regular throws, in case of one example channel, noticeable differences are found. This method to create a model for a good throw is easy to implement. However, taking average of event type data has disadvantages like synchronization problems and it might turn out that some essential features are lost due to averaging. Further studies are, however, needed to find out if the flaws in technique can be truly detected in this way and if there is a point to compare the measurements results of two different javelin throwers.

5. CONCLUSIONS

A custom-made pair of capacitive force sensor insoles was designed and manufactured to fit into track shoes. The measurement system, consisting of the insoles, the read-out electronics and the wireless link, were tested during a javelin throw training sessions. The examples of the possible data processing methods for the javelin throw data were proposed. This preliminary testing indicates that, with some improvements, this measurement method can be utilized to capture the force distribution and timing data under the sole in sport applications. In the case of the javelin throw event, the measurement of the forces during the instant of the release phase of the throw seems very promising. This data can be used to figure out how the athlete operates the block leg. The role of the block leg is one of the most important components of a successful throw. The monitoring the block leg is challenging because the final step only lasts a few hundred milliseconds. By using a regular video camera, this event lasts only a few frames. The system that we are developing is indented to use as a coaching tool to measure distribution, relative magnitudes and timing of the forces between a foot and a shoe during sport events.

ACKNOWLEDGMENTS

We want to thank Pekka Iso-Ketola from the TUT Kankaanpää Unit for the cooperation in the development of the insole. We also want to thank Rami Lehtinen, Teemu Ylilauri, Esa Utriainen and Sanni Utriainen for the testing and advice on the sport aspect of this work.

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