Monitoring of Carried Weight During Walk Using a Wearable Pedobarography System

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***Abstract*— Personal health monitoring is advantageous in heavy work environments to reduce the risk of wear and tear and acute injuries. The study of forces between the plantar surface of the foot and a supporting structure, pedobarography, is a promising candidate for monitoring carried weight during walk. The aim of this study was to evaluate the cost effective pedobarography measurement system, IngVaL. Two aspects are evaluated, namely, how well IngVaL can monitor carried weight during walk and if the novel implementation increased the durability. Fifteen test persons made five treadmill walks with a carried weight of 10, 20, 0, 15, and 5 kg. The equipoise analysis method was used. The Root Mean Square Error (RMSE) for estimation of the carried weight was 13.8 kg. A study with the earlier version of the measurement system had a RMSE of 23.3 kg. The earlier system, as well as commercial systems using this kind of sensors, have problems with sensor durability. The new sensor implementation, where the active sensor area boundary was no longer affected by mechanical stress, resulted in no broken sensors. This study shows an increased performance of carried weight estimation compared with earlier work, together with an improved sensor durability.**

Keywords- pedobarography; carried weight; portable; wearable; insole; in-shoe.

I. Introduction

Pain in the lower back is one of the most common health problems today and is expected to become even more frequent in the future [1]. About a third of all employees in Sweden, during the year 2015, had pain in their lower back every week [2]. Heavy work load and the total amount of lifted weights and lift frequency are moderate to strong risk factors for lower back pain [3]. The year 2015, 16% of the employed men and 10% of the employed women in Sweden lifted more than 15 kg several times a day [2]. The carried weight will vary during the work time.

Monitoring of the conditions in heavy work environments is important to reduce the risk of wear and tear and acute injuries. A wearable system would make it possible to monitor workers that are not stationary.

Pedobarography, the study of forces acting between the plantar surface of the foot and a supporting surface, has been used for weight estimation while standing still [4] and is a promising candidate for estimation of carried weight while walking [5]. IngVaL (Identifying Velocity and Load) [6] is a pedobarography measurement system designed to be a robust and low cost system for monitoring of health related walk parameters. IngVaL is an improved design of an earlier research prototype. The earlier system has been validated for monitoring of walking speed [7] and carried weight [5].

The aim of this study was to evaluate the cost effective pedobarography measurement system, IngVaL. Two aspects are evaluated, namely, (1) how well IngVaL can monitor carried weight during walk and (2) if the novel sensor implementation can make the sensors more durable.

In Section II, the methods for this study are explained. Results are presented in Section III. Section IV is the discussion and the conclusion is in Section V.

II. Methods

The design of this study was cross-sectional. This section is split into the three sub-sections of hardware, experiment setup and data analysis.

A. Hardware

The IngVaL system consists of sensors (force sensing resistors), electronics for signal conditioning and a microcontroller based data acquisition unit. The data was sent via Bluetooth 4.0 to a Windows tablet.

Four force sensing resistors of model A401 (Tekscan Inc., Boston, MA, USA) are sandwiched in each shoe insole between a base foundation made of Ethylene-Vinyl Acetate (EVA), cork, and leather as upper layers for protecting the sensors and also providing a comfortable, less perspiration inducing, interface with the foot. EVA is a firm but flexible material that is often used in sports equipment and insoles.

The heel, the lateral and medial sides of the metatarsal pad and the big toe pad were chosen as locations for the sensors, see Figure 1. The sensor locations are chosen like this due to the bone structure of the foot. Each sensor has a boundary for the active sensor area and this boundary is sensitive for mechanical stress that can short-circuit and damage the sensor. An earlier prototype of the insoles had problems with sensor durability due to mechanical stress on the boundary of the active sensor area. Besides the higher risk of sensor damage, there were also some peaks in the data from the prototype system due to the short-circuiting of the sensors.

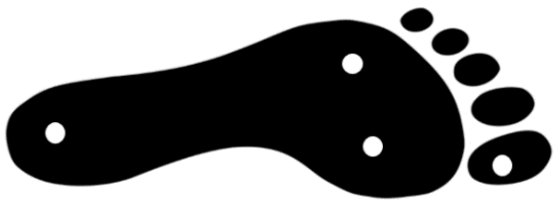

Figure 1. Showing the location of the four insole force sensing resistors located at the big toe, the inner and outer metatarsal pad and the heel.

In version two of the system, called IngVaL, EVA material was removed directly under the sensor's boundaries to prevent the mechanical stress and resulted in a disc structure under each sensor's active sensor area. The block diagram, from force sensing resistors to the data analysis, for the IngVaL system, is shown in Figure 2.

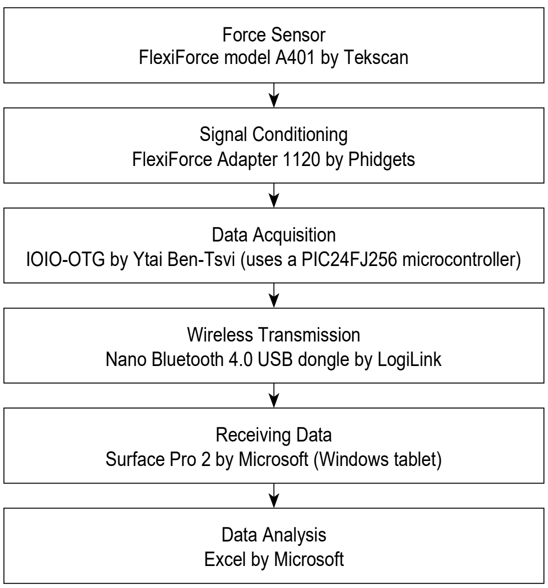

Figure 2. Block diagram for the IngVaL measurement system.

A dynamic calibration was used since the application is to measure during walking conditions [8] and the calibration functions were chosen as fourth order polynomials [9]. A Tedea-Huntleigh 1006 single point load cell (Vishay Precision Group, Malvern, USA) was used for the calibration of the force sensing resistors and the cell was in turn calibrated by using calibrated weights. The calibrating force was applied perpendicular to the active sensor area.

The data sampling (at 200 Hz) and wireless data transmission were made using an IOIO-OTG (SparkFun Electronics Inc., Niwot, CO, USA) which is based on a PIC24FJ256 microcontroller. The name IOIO-OTG comes from naming the first device IOIO, since it has many inputs and outputs, while OTG refers to the Universal Serial Bus (USB) standard On-The-Go (OTG). The IOIO-OTG was connected to the two insoles using elastic cables, secured with Velcro straps, around the ankle and around the lower thigh. A modified version of the java program ioiometer-pc [10] received and saved the data on a Windows tablet.

B. Experiment Setup

Fifteen test persons were recruited from the university staff. The test persons had an average weight of 83.9 kg. Inclusion criteria were that they had European Union (EU) shoe size 43-44, were healthy and able to walk naturally when carrying the extra weight. All test persons used the same shoes with the insoles inside, including force sensing resistors. All the test persons performed five walks at a speed of 1.0 m/s on a treadmill (Comfort Track Prime 97690, LifeGear Ltd., Taiwan) after an initial test walk to see that all sensors were activated and that the test person felt comfortable walking on a treadmill.

During each walk, the test persons carried a backpack loaded with a pseudo-randomly chosen extra weight of 10, 20, 0, 15, and 5 kg, see Figure 3. The first author is shown walking on the treadmill with the shoes, including the insoles with the sensors, and with the backpack loaded with extra weight. Extra padding was used inside the backpack along the spine to reduce the risk of injuries.

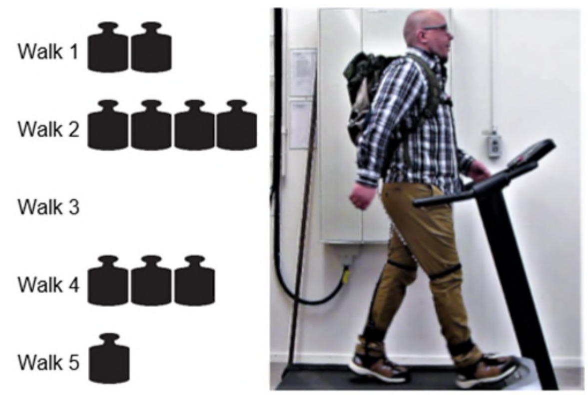

Figure 3. Each test person made five walks with different amount of carried weights (each black weight symbol represents 5 kg).

Data was recorded from the sensors in the pedobarography system during one minute per walk. Acceleration and deceleration phases were not part of the recorded data. The reference weight was measured using a GS 42 BMI electronic floor scale (Beurer GmbH, Ulm, Germany).

C. Data Analysis

The estimation of carried weight was made using the equipoise method [5]. Equipoise happens once during each stance phase (between heel strike and toe-off) and is defined as 0.5 when half of the weight is distributed on the heel sensor and the other half on the forward sensors. Examined data was chosen in the equipoise range of 0.5±0.1. Data samples are chosen if no weight was on the other foot at the same time to make sure all weight was on one foot. Microsoft Excel was used to calculate an average of the forces for the equipoise samples.

Figure 4 shows an overview of the three steps of the data analysis: (1) calculate the equipoise ratio, (2) select data in the 0.5±0.1 equipoise range when only one foot is in contact with the ground, and (3) calculate the average force and then calibrate for each individual.

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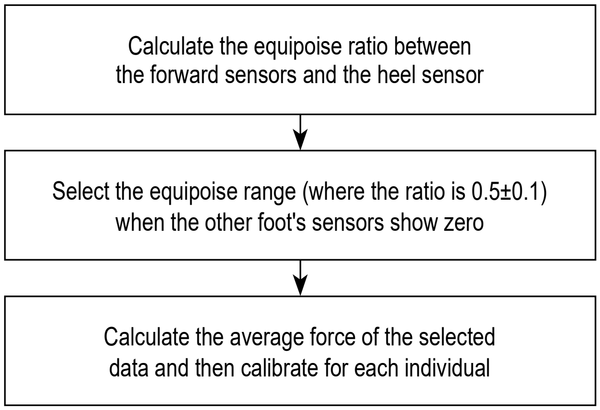

Figure 4. Overview of the three steps of the data analysis.

Two different methods were used for doing the individual calibration. Method 1 used the walk without extra added weight while method 2 also added the maximum carried weight (20 kg). The estimated carried weight was then subtracted with the known weight as measured with a reference floor scale to calculate the error. Finally, the root mean square errors were calculated.

III. Results

The root mean square error was 17.2 kg when method 1 was used and 13.8 kg when method 2 was used, see Figure 5. Dots show errors using the walk without extra carried weight for the individual calibration. Circles show errors when also using the maximum carried weight (20 kg) for individual calibration. There are 15 fewer dots for method 2 since double the amount of data is used for the individual calibration.

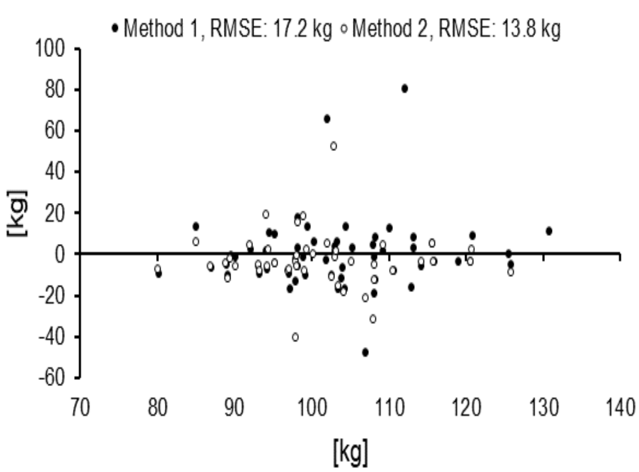

Figure 5. Reference weight (measured with a floor scale) versus weight estimation errors.

None of the sensors broke during more than 350 minutes of walking, as well as taking off and putting on the shoes 15 times.

IV. Discussion

Personal health monitoring using wearable measurement systems is a promising way to be able to monitor health outside of the hospital setting [11][12].

The pedobarography system, IngVaL, is designed to be a robust and low cost measuring system for monitoring of health related walk parameters. The aim of this study was to evaluate the cost effective pedobarography measurement system IngVaL. Two aspects are evaluated, namely, (1) how well IngVaL can monitor carried weight during walk and (2) if the novel sensor implementation can make the sensors durable. The improvements from the first version of the system are mainly in the sensor implementation and sensor calibration. The improvement in the analysing method is how the analysis also uses the maximum carried weight for calibration.

This study used 15 test subjects and five different carried weights for a more thorough experimental examination than in an earlier study where ten test subjects and three different carried weights were used [5]. The same equipoise method was used in this study and resulted in a RMSE of 17.2 kg. A further method improvement resulted in a RMSE of 13.8 kg. This was a good improvement from 23.3 kg in the earlier study (recalculated because Mean Average Error (MAE) was used in that publication). This shows that the new system version (IngVaL) performed better than the previous prototype system. There is, however, room for improvement, and one possibly way to reduce the RMSE is to improve the data analysis. One challenge is to keep the thickness of the insole from becoming larger than a normal insole. The current insole is similar to a normal insole and has a thickness around 5-6 mm.

To the best understanding of the authors, there are no other wearable systems for monitoring carried weight while walking. There is, however, related work where the estimation was made after coming to a standstill after walking and that study presented a RMSE of 10.5 kg using nine test subjects [4]. The need of standing still during measurement makes it unsuitable for monitoring during a workday to see the load of the work over time.

Forces are distributed proportionally over all regions of the foot regardless of foot arch type [13]. This enables the use of fewer sensors instead of a more expensive sensor matrix. It is important to design a durable system for monitoring of heavy work environments. IngVaL used a new way of implementing the sensors into the insoles and this made them more durable. This resulted in no broken sensors during more than 350 minutes of use. Four sensors broke during 80 minutes, when using the earlier version of the system. Sensor replacement would also mean that a new calibration of the sensor is needed and this is a concern if the system is to be commercialized in the future. The durability issue made the earlier prototype system unsuitable.

A potential limitation in this study could have been the use of a treadmill, which might result in a less natural walking style compared to on a flat floor. On the other hand, the equipoise is measured when one foot has equal pressure on the forefoot sensors and the heel sensor while the other foot is in the air. This part of the stance phase (when the foot is in contact with the ground) is expected to be minimally, if at all, affected by walking style because the foot is not in direct motion during this particular moment. The treadmill is instead an advantage since it allows a constant walking speed of 1.0 m/s. In order to avoid the influence of different types of shoes, all of the 15 test subjects in the study used the same shoes during the measurements. They also used the same insole in the shoes.

The IngVaL system has earlier shown to be able to measure walking speed. Together, monitoring of the carried weight and the walking speed, enable estimation of energy expenditure [14][15].

V. CONCLUSION

In this study, the cost effective pedobarography measurement system called IngVaL has been evaluated considering two aspects, namely, (1) how well IngVaL can monitor carried weight during walk, and (2) if the novel sensor implementation can make the sensors durable. This study shows that the root mean square error has been decreased from 23.3 kg to 13.8 kg and validates that the new measurement system version (IngVaL) performs better than the previous system regarding monitoring of carried weight during walk. The new implementation of the sensors has made them more durable and resulted in no broken force sensing resistors during the experiment.

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REFERENCES

[1] D. Hoy et al., "A systematic review of the global prevalence of low back pain," Arthritis Rheum., vol. 64, pp. 2028-2037, 2012.

[2] The Swedish Work Environment Authority (Arbetsmiljöverket), Arbetsmiljöstatistik 2016:2, 2016.

[3] H. Heneweer, F. Staes, G. Aufdemkampe, M. van Rijn, and L. Vanhees, "Physical activity and low back pain: a systematic review of recent literature," Eur. Spine J., vol. 20, pp. 826-845, 2011.

[4] N. A. Sazonova, R. Browning, and E. S. Sazonov, "Prediction of bodyweight and energy expenditure using point pressure and foot acceleration measurements," Open Biomed. Eng. J., vol. 5, pp. 110-115, 2011.

[5] P. Hellstrom, M. Folke, and M. Ekström, "Wearable Weight Estimation System," Procedia Com. Sci., vol. 64, pp. 146-152, 2015.

[6] P. A. R. Hellstrom, A. Åkerberg, M. Ekström, and M. Folke, "Evaluation of the IngVaL Pedobarography System for Monitoring of Walking Speed," J. Healthcare Informatics Research, vol. 24, pp. 118-124, 2018.

[7] P. A. Hellstrom, A. Akerberg, M. Ekstrom, and M. Folke, "Walking Intensity Estimation with a Portable Pedobarography System," Stud. Health Technol. Inform., vol. 224, pp. 27-32, 2016.

[8] J. Florez and A. Velasquez, "Calibration of force sensing resistors (fsr) for static and dynamic applications," 2010 IEEE ANDESCON, Year, pp. 1-6.

[9] J. M. Brimacombe, D. R. Wilson, A. J. Hodgson, K. C. Ho, and C. Anglin, "Effect of calibration method on Tekscan sensor accuracy," J. Biomech Eng., vol. 131, pp. 034503, 2009.

[10] Johannes Rieke, ioiometer-pc (for Windows), in https://github.com/jrieke/ioiometer-pc, 2016.

[11] B. H. Dobkin and A. Dorsch, "The promise of mHealth: daily activity monitoring and outcome assessments by wearable sensors," Neurorehabil. Neural Repair, 2011, pp. 788-798.

[12] K. Hurt, R. J. Walker, J. A. Campbell, and L. E. Egede, "mHealth interventions in low and middle-income countries: a systematic review," Glob. J. Health Sci., vol. 8, pp. 183, 2016.

[13] S. L. Goffar et al., "Changes in dynamic plantar pressure during loaded gait," Phys. Ther., vol. 93, pp. 1175-1184, 2013.

[14] G. J. Bastien, P. A. Willems, B. Schepens, and N. C. Heglund, "Effect of load and speed on the energetic cost of human walking," Eur. J. Appl. Physiol., vol. 94, pp. 76-83, 2005.

[15] J. M. Falola, N. Delpech, and J. Brisswalter, "Optimization Characteristics of Walking with and without a Load on the Trunk of the Body," Percept. Mot. Skills, vol. 91, pp. 261-272, 2000.

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