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Virtual Conference

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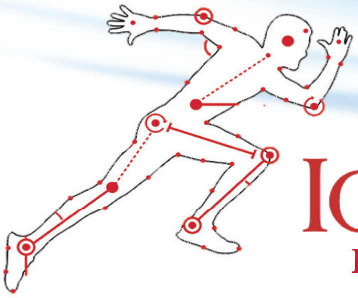
Abstract**Book**



IOWA STATE UNIVERSITY

Department of Kinesiology College of Human Science

Welcome

from Symposium Co-Chairs

Dear Symposium Participants,

We hope that all of you have been healthy and safe during the time of pandemic. With your persistent supports, the XVI International Symposium on 3D Analysis of Human Movement (3D-AHM) will be held with a virtual format on May 25-28, 2021. This symposium features scientific presentations by authors from a total of 15 countries worldwide. Iowa State University, the College of Human Sciences, and the Department of Kinesiology are proud to present this symposium proceedings. The symposium theme of “From Data to Discovery: Evidence-Based Approaches” has a synergism with our University motto of “Science with Practice”. Both strive to link the scientists who contribute to a body of knowledge to the practitioners who utilize that knowledge. The symposium that we have hosted was our effort to facilitate this process. We designed a forum that encouraged international communication and will, ultimately, lead to the betterment of society. These abstracts are the result of countless hours of intellectual thought and tedious work. We hope that you will take the knowledge gained from this labor and apply it to your research, practice, or teaching so that the rewards of the scientific process can be fully realized.

Sincerely,

Li-Shan Chou, PhD

Tim Derrick, PhD

Evaluation of an instrumented insole for the assessment and monitoring of walking performance

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Abstract- Analysing the ground reaction force (GRF) is an important component in rehabilitation medicine evaluation. Force plate measurements remain the gold standard but wearable systems are gaining precision and reproducibility allowing for relevant in-field analysis. The Gait-Teacher custom made by Rehabshop (Belgrade), is an insole with embedded industrial quality pressure sensors and one 3D inertial measurement unit (IMU). Typically, coupling the pressure sensors and IMU may help in assess the GRF. The hypothesis was that from the instrumented insole data we can estimate the horizontal and vertical components of the GRF during the loading and push-off phases of the gait cycle. One healthy subject was walking at self-selected pace and data from the wearable system were validated against reference data obtained from a motion analysis system and a force plate. We found that the insole could estimate correctly the GRF during the loading phase but not during the push-off phase, probably due to the need to further optimize sensor position in the insole.

Keywords- instrumetned insole, motion analysis, ground reaction force, horizontal component, vertical component,

1. INTRODUCTION

Wearable systems for the assessment of the movement are being much improved due to availability of new materials and miniaturization of electronics with high computing power and wireless communication. At this point there are many gait assessment insoles [1], but most of those use force sensors with hysteresis, delay and insufficient robustness to the changes of temperature and humidity. Many of those can be used for the assessment of gait data, but there is no device that can provide versatile ground reaction force data comparable with the data from force plates. The Gait Teacher (Rehabshop, Belgrade) which is an insole instrumented with five industrial pressure sensors and an inertial measurement unit (IMU) has been developed to cope with these problems.

The potential of this instrumented insole has not been thoroughly evaluated so far, especially for gait analysis. Due to its design with multiple pressure sensors rather than a pressure map, the ability of the insole to capture the whole amplitude of the ground reaction force (GRF) was to be evaluated. Moreover, thanks to the incorporation of an IMU, the possibility to obtain more information than just the GRF amplitude was also to be tested. It was hypothesized that a reliable estimation of both vertical and horizontal components of the GRF might be obtained from the projection of the sum of the different pressure sensor measurements on the vertical and horizontal directions of the ground during the loading phase and the push-off phase. During the remaining part of the stance, foot flat phase, the insole tends to be parallel to the ground; hence the method used cannot be applied to estimate the horizontal component of the GRF.

To test this hypothesis, several evaluations were performed with one subject walking at self-selected pace, wearing the insole while being simultaneously measured with a motion capture (MoCap) system and a force plate. First, the amplitude of the GRF obtained by the insole (pressure sensors data) and the force plate were compared. Second, the orientation of the foot obtained by the insole (IMU data) and the MoCap system were compared. Third, the vertical and horizontal components of the GRF obtained by the insole (pressure sensors and IMU data) and the force plate were compared.

2. MATERIAL AND METHODS

Insole design

The custom designed insole comprises 19 mm diameter pressure sensors with a measuring range from 0 to 3.5MPa. These sensors are based on a gauge measuring absolute presser and packaged into a full stainless steel 316L. The sensor characteristics are the following: linearity <+/-0.25 %FS, BFSL, repeatability <+/-0.075 %FS, hysteresis <+/-0.05 %FS, zero thermal error < 1.0 %FS,@250, stability error < +/-0.2 %FS/year. Five of these

sensors were embedded in a 7-mm thick evo-rubber insole on the following position: heel lateral (HL), heel medial (HM) first and fifth metatarsal head (FM1-FM5) and on the hallux (HAL) as shown in Figure 1.
An IMU was embedded into the insole near the heel forces sensors. This IMU was a MPU-6050 (16-bit conversion). The IMU measures the acceleration and the angular rate in the range ±4g and ±500 deg/s, respectively. Only first 14 bits were used with the intention to minimize the noise. The orientation of the IMU transducers was the following: z axis points up, x axis points forward, and y axis points medially. The angular rates are ω_x – angular rate orthogonal to the insole (frontal plane) directed from heel to toe, ω_y – orthogonal to the insole and the direction heel-toes pointing laterally, the direction is in the plane of the insole and orthogonal to the direction of the insole, and ω_z – angular rate in the plane of the insole pointing up. Both the pressure sensors and the IMU had an acquisition frequency of 50Hz.

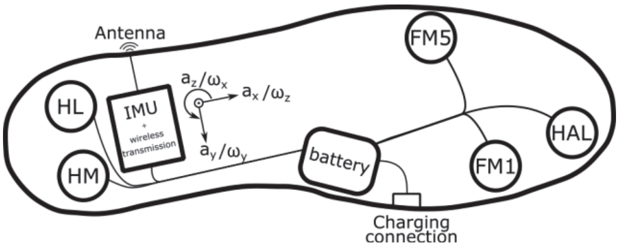

Figure 1. Insole design

Data collection and processing

The acquisition was performed using an Optitrack 10 camera Mocap system with a 100 Hz frequency. Three 8 mm cutaneous markers were positioned on each foot on the calcaneum and the first and fifth metatarsal head. The foot frame was then defined following ISB's recommendation [2]. GRF was then registered using a 1000 Hz AMTI force plate synchronized with the MoCap system. For calculating the sagittal position of the foot, the data extracted from the IMUs were also used. In order to minimize the integration time, as we were studying asymptomatic walk, it was supposed that when all the force transducer except the hallux was above 10 N that the foot was in a flat position and that the angular position could be calculated downward and forward from this point by integrating the angular velocities around the y axis (ω_y) using the trapezoidal method.

The projection of the forces was done considering the forces obtained from all the pressure sensors perpendicular to the foot horizontal plane and then projected on the global frame on the vertical and on the horizontal (i.e. anterior-posterior) axes.

Subject

One subject (male 29 years old 73 kg) with no known motor disorder was asked to walk at self-selected pace on a 10 m horizontal walk path. The subject was instrumented with two insoles glued on its right and left shoe soles to minimize the error arising from relative motion of the insole with respect to the foot when wearing the insole in the shoes. The foot insole output was calibrated using the body weight of the subject as the sum of all forces acquired during still standing.

Statistic

The force and orientation obtained by the insole were compared separately as well as altogether (i.e. for the estimation of the vertical and horizontal components) with force plate and MoCap system measurements. For each comparison, the root mean squared errors (RMSE) and the maximal error with the reference measurements was computed for each trial. As the subject was asymptomatic, all results from the left and the right foot were considered the same and averaged. Five trials were retained for each side. The mean value ±1 standard deviation was then calculated. In order to be able to evaluate the relative error, the mean value of the orientation or force ± 1 standard deviation was also given. In addition, the mean force ±1 standard deviation at the different pressure sensors, their total sum and the GRF amplitude measured with the force plate was plotted on Figure 2 (a). Secondly, the total force measured by the insole projected on the global vertical and horizontal axes were plotted respectively on Figure 2(b) and Figure 2(c).

3. RESULTS

Orientation Angle

The error on the foot sagittal angle with respect to the ground is low considering the mean RMSE of 3.3° and maximum errors value of 10° compared to the mean range of motion of 86°. As a result, force projections on both vertical and horizontal axes obtained either from the MoCap system or the IMU data tend to be similar as seen on Figure 2(b,c).

Amplitude

As seen on the Figure 2(a), the errors on the force amplitude tend to be mainly on the second half of the stance during the second peak of GRF. The insole tends to underestimate the force compared to the force plate. On the first half of the stance phase the force measured from the insole comes mainly from the heel lateral and medial pressure sensors and on the second half mainly from the first and fifth metatarsal and the hallux.

Table 1. Root mean square error, max error and amplitude of the reference value fo r

	RMSE Mean±std	***Max Mean±std***	***Amplitude (range of motion) Mean±std***
Angle IMU vs Mocap (°)	3±3°	10±6°	86±5°
Force amplitude (insole vs. force plate, in N)	112±20 N	328±51 N	919±25 N
Force vertical component (insole with orientation from Mocap vs. force plate, in N)	111±18 N	305±72 N	919±25 N
Force vertical component (insole with orientation from IMU vs. force plate, in N)	112±20 N	310±69 N	919±25 N
Force horizontal component (insole with orientation from Mocap vs. force plate, in N)	49±18 N	184±105 N	307±22 N
Force horizontal component (insole with orientation from IMU vs. force plate, in N)	54±11 N	166±56 N	307±22 N

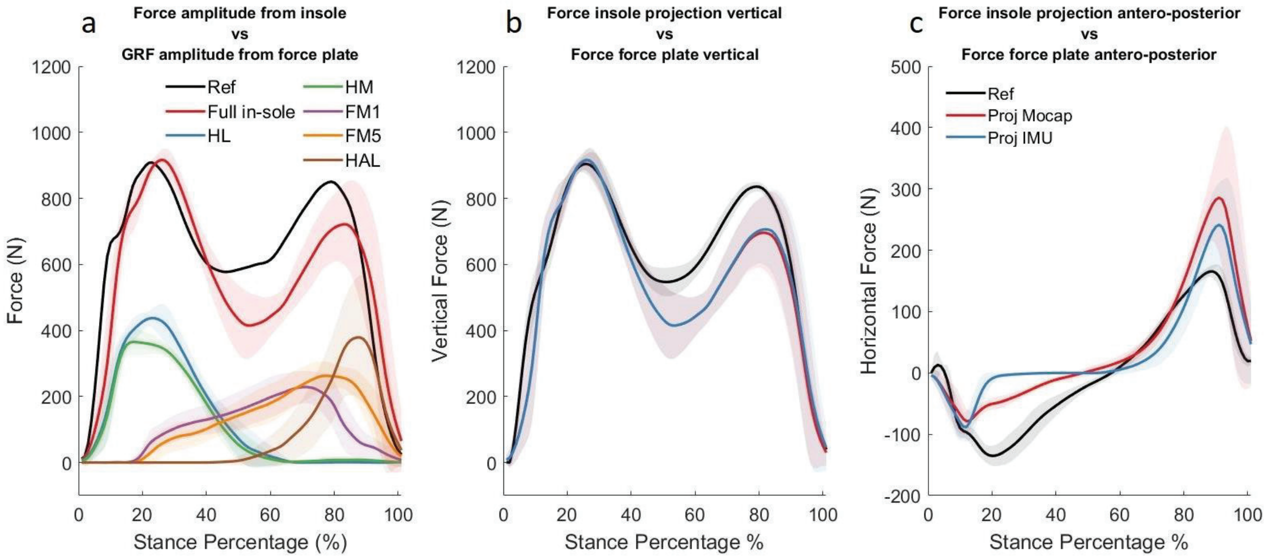

Figure 2. Comparaison of the GRF estimate from the insole and force plate

Force vertical component

For the vertical component, the error tends to represent at maximum 33% of the maximum amplitude for both the projection with the orientation form MoCap system and IMU data. In addition, as seen on Figure 2(b) the standard deviation tends to be higher on the second half of the stance phase which correspond to the propulsion phase.

Force horizontal component

For the horizontal component, the maximum error also represents 33% of the mean amplitude. However, this time, the insole tend to overestimate the force horizontal component on the second half of the stance phase although the force amplitude tends to be lower during this part of the stance phase. During the second half of the stance phase, the time at which the projected force is increasing seems to be synchronized with the time the force measured by the force plate is switching from anterior to posterior direction.

4. DISCUSSION

Firstly, as the error between the foot orientation measured by the MoCap system and the IMU seems low, the following discussion will be only focusing on the projection of the GRF using the IMU. In this preliminary study, the orientation is simply obtained by time integration of the angular velocity and more accurate algorithm such as Kalman filter [3,4] can be implemented in future studies.

Considering the overall error on force amplitude of 111N obtained in this study, it seems that the insole provide a good estimation of the GRF during the whole stance phase. Errors mainly arise during the second part of the stance phase after the full contact of the foot with the ground. It might be due to a non-optimized positioning of the pressure sensors. Indeed, the peak of pressure under the foot tend to be under the second metatarsal head in asymptomatic gait [5]. As there is only two force sensors under the first and fifth metatarsal head, a significant part of the GRF might be transferred through the insole material. A solution would be to use a different positioning of the sensors under the foot or eventually additional sensors. Determining the position and number of force sensors shall be optimized based on the minimization of the tracking error from the typical trajectory of the center of pressure. In this condition, it could be expected to reduce the overall error to the RMSE find during the first part of the stance which is 66 N. Thus, it seems that the two sensors on the heel are enough to estimate the GRF while the three on the front part of the foot, at least with their current position, are not.

Considering the force projection on the different axes, the results obtained for the force vertical component are similar to the one obtained with the GRF amplitude. However, for the force horizontal component, the results seem to estimate correctly this force only during the brief period before the full flat phase (contact on the ground of HL HM FM1 and FM5) which correspond to the loading response. After, as expected during the foot flat phase, it is impossible to estimate any horizontal projection as the foot is parallel to the ground. However, at the end of stance, the force horizontal component obtained from the insole seems to be synchronized with the one measured from the force plate but tends to overestimate it. The overestimation might be due mainly to the position of the IMU near the heel which cannot capture the real orientation of the FM1, FM5 and HAL sensors. The same issue arises for the modeling of the foot with one rigid segment and the error between the foot orientation measured by the MoCap system and the IMU is therefore limited. As for model of the foot with multiple segments [6], it could be hypothesized that using a second IMU in the front part of the foot, near the metatarsal head and to use it during the second part of the stance to evaluate the position of the foot might allow a better estimation of the force horizontal component. As for the additional pressure sensors, this solution is not trivial form a technical point of view as it would require modifying the whole electronics of the insole. Even if the insole does not allow to thoroughly measure the force horizontal component during the foot flat phase, it seems that it can, at least, estimate the loading phase and the propulsion phase. Thus, our initial hypothesis is partially verified.

As a result, it seems that this insole embedding five pressure sensors and an IMU could be a reliable tool to be integrated in the ecologic evaluation of a lab or a clinic. It must be noted that this study is only a preliminary one and it would be needed to be performed on more asymptomatic subjects and extended to pathologic subjects to confirm the results. It could be interesting to also consider typical gait patterns found in rehabilitation centers such as foot drop and toe walker in order to validate these insole in a clinical context.

5. ACKNOWLEDGEMENT

Professor Dejan Popović is the head of RehabShop (https://rehabshop.rs/), a start-up company that is developing the instrumented insole.

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