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PAPER

ASPEBI: A MATLAB Tool for Motion Analysis of Non-Specific Low Back Pain Patients

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ABSTRACT

Low back pain is one of the most common health issues worldwide, and non-specific low back pain (NLBP), whose causes are unknown, represents 85% of these cases. Hamstring Extension in Bipedal Position (PEBI) is a clinical sign designed to discriminate the cause of the pain of NLBP as of muscular origin due to the stiffness of the hamstring. Currently, PEBI lacks quantitative assessment, which is required to be utilized in primary care. To support the process of getting such information, in this work, we present ASPEBI, a customized MATLAB® app developed to provide researchers and clinicians with a tool for the visualization of the kinematic and spatiotemporal gait parameters of patients examined with PEBI. This objective information is processed from data collected with the Xsens MTw Awinda system, which can be analyzed by the final users. Lastly, this tool is user-friendly with a modular design that allows integration of other physiological technologies to conduct multimodal analysis, and it could be utilized to explore issues related to older populations or populations with neurodegenerative diseases, among others.

KEYWORDS

gait analysis, non-specific low back pain, MATLAB®, Xsens MTw Awinda®

1 INTRODUCTION

Low back pain (LBP) is the leading cause of work disabilities worldwide and one of the most common musculoskeletal health conditions that affects people of all ages [1, 2]. More than 85% of LBP cases have an unknown etiology, making its diagnosis and treatment challenging. Such cases are categorized as non-specific low back pain (NLBP), a condition that has been extensively studied due to the high need of identifying its possible causes [3]. Several studies have shown that one of the causes of NLBP may be associated with hamstring stiffness [4–7]. For instance, Hernandez et al. [7] presented the clinical test named Hamstring Extension in Bipedal Position (PEBI, its acronym in Spanish) aimed to determine whether or not the pain may be caused by hamstring stiffness. The test has been successfully studied for over

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ten years with 183 patients; however, this assessment is mainly based on doctors' observations and lacks quantifiable measurements of the patients, such as mobility performance, which could permit specialists to include the test in primary care.

Mobility performance is commonly evaluated by conducting gait analysis using technologies such as vision-based systems and, more recently, wearable inertial sensors. Currently, commercial inertial systems (e.g., Xsens MVN® and Tech-MCS Studio 4®) may include visualization and kinematics parameters processing of the human body, e.g., joint angles, velocities, accelerations, and other gait parameters; nevertheless, such systems can be costly for specific needs. As an alternative, open-source software has been presented as a solution, nonetheless, its use can be time-consuming for non-technical experts and those developments may still be in their infancy (OpenSim, MoComp®) [8]. Likewise, studies have presented low-cost motion capture systems based on inertial sensors for real-time human motion analysis, using visualization tools such as Blender game engine and Unity3D [9, 10]; however, these require more research given that they are not suitable for high-precision kinematic analysis which is essential for clinical applications.

In this paper, we present a Matlab tool to obtain quantifiable motion information of NLBP patients examined with the PEBI test using the data recorded with the Xsens MTw Awinda® system. We designed a customized Matlab app named ASPEBI to support both healthcare professionals and researchers in the PEBI execution and its subsequent analysis. It provides a detailed guide to conducting the test correctly; it is adapted to register information such as socio-demographic data according to regulations of clinical patient registration [11], e.g., subject's health condition, height, weight, etc.; and it provides information for research needs. In addition, using a simple avatar, the app allows 3D reproduction of the patient's lower limbs movements captured with the Xsens MTw Awinda® system. Lastly, the application can provide a report with graphs and spatiotemporal parameters of the gait prior to and post-PEBI execution, such as step length or joint angles. Thereby, ASPEBI assists physicians or researchers to identify differential gait factors in NLBP patients who executed the PEBI.

2 PEBI DESCRIPTION AND SPATIOTEMPORAL PARAMETERS

PEBI is a clinical sign that is easy to reproduce by health professionals and aims to differentiate NLBP that may have a muscular origin due to contraction of the hamstrings. In the PEBI test, the patient is initially in a bipedal position; Next, the subject raises a leg and rests it on a 30 cm high surface with a hip flexion of approximately 30°, the knee must be fully stretched with the maximum tolerated dorsiflexion of the ankle. Then, the patient must remain in this position for one minute and perform the same procedure with the other leg. Finally, the subject is asked to walk 10 meters and is asked about their level of pain. If the pain decreases or disappears, the sign is considered positive, that is if the pain is of muscular origin and the corresponding rehabilitation is carried out.

In order to obtain objective-quantifiable information on the person's mobility, we have conducted an experimental protocol to obtain and analyze gait parameters such as stride length, stride width, cadence, or speed, and kinematic parameters before and after performing the PEBI.

In our experimental protocol, we recruited three healthy subjects (one female participant and two male participants) with an age and height range of 21 to 49 years and 1.50 to 1.83 meters. Figure 1 shows the sensor locations: one sensor in the pelvis, one sensor in the mid-thigh of each leg, one sensor in the medial area below the knee of each leg, and one sensor on the dorsum of each foot. Next, the participants were asked to initially stay in a standing position at the starting point, then walk 10 meters until reaching the indicated final position, where they must perform the PEBI and then return to the initial position.

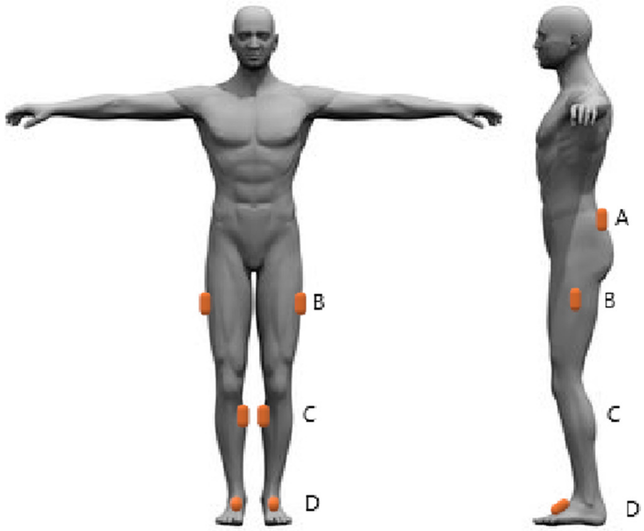


Fig. 1. Sensors' location of the Xsens Awinda system to record kinematics data of individuals of lower limbs

3 ALGORITHM TO DETERMINE SPATIOTEMPORAL PARAMETERS OF GAIT

The MVN Analyze software is the main tool to process the data collected with the Xsens MTw Awinda® system. Whereas this software provides information of the kinematics parameters of the subject, it does not provide specific information of the gait parameters that practitioners may need. Therefore, we have developed an algorithm to determine spatiotemporal parameters of gait including step length, stride length, gait speed, and cadence.

The algorithm was designed by leveraging the information provided by the MVN Analyze software through the *.mvnx* file which is generated when data are collected. More specifically, the algorithm determines the spatiotemporal parameters using only the data from the sensors located in the feet (see Figure 2). Hence, the gait phases are identified, and the foot contact phase is used to estimate each parameter, as illustrated in the diagram in Figure 3.

Fig. 2. Sensor on the foot from which data are extracted to obtain the gait spatiotemporal parameters

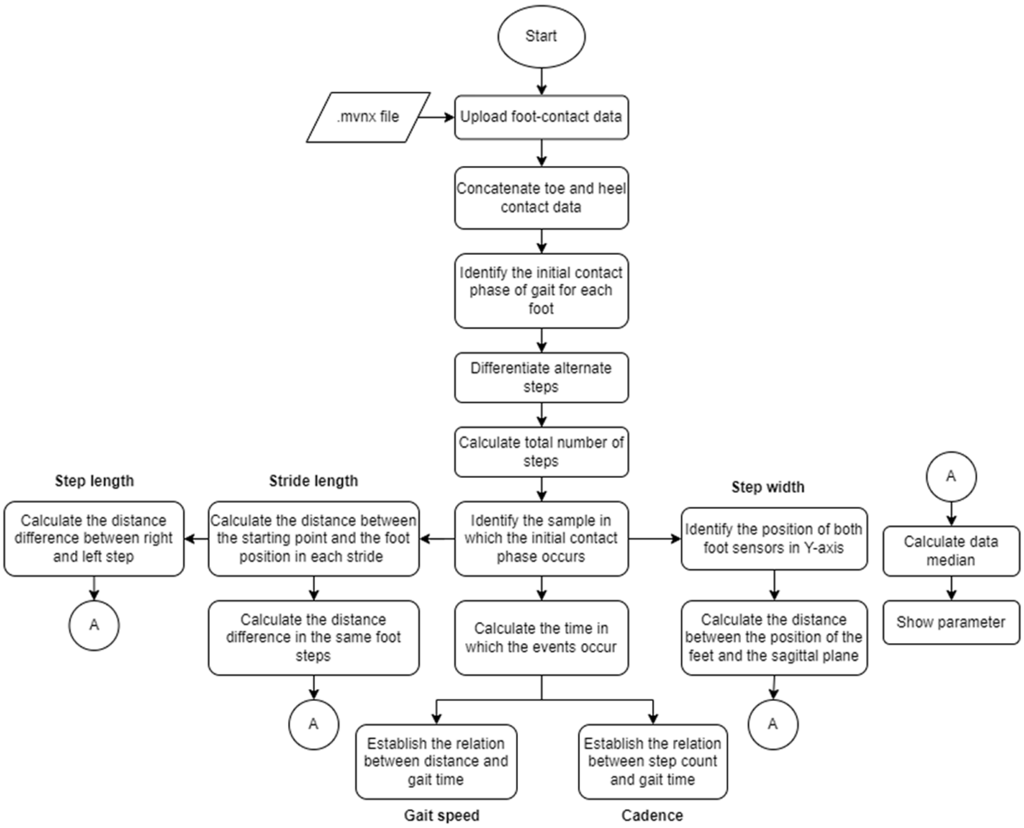


Fig. 3. Algorithm to determine the spatiotemporal parameters of gait [12]

To evaluate the algorithm's performance, we used the mean of the error rate (*e*), which is the mean of the difference between the obtained and the expected value of the parameter. The error rate is calculated as follows:

$$e = \frac{p_{obt} - p_{exp}}{p_{exp}} x100$$

where, *e* is the error rate, p_{obt} is the obtained value of the parameter, and p_{exp} is the expected value of the parameter. The expected values were calculated based on foot contact. Namely, the subjects walked 10 m over a paper with the soles of their shoes impregnated with ink, which allowed us to identify the foot contact to be used to obtain the expected values of the spatiotemporal parameters, i.e., step length, stride length, stride width, gait speed, and cadence [12].

4 ASPEBI SOFTWARE DESCRIPTION

ASPEBI is a desktop application developed in MATLAB R2021b for motion visualization and analysis of kinematic data of patients with NLBP examined with the PEBI test. The user interacts with the graphical user interface (GUI) according to his or her role, i.e., health professional or researcher, who is smoothly guided to collect and/or process the data. Namely, ASPEBI guides the user on how to properly collect the data that corresponds to the protocol aimed to assess the effects of the PEBI in the subjects' gait (see Section 2) using the MTw Awinda® motion capture system from Xsens. Those data are then stored in a *.mvnx* extension file that can be used in the processing phase in order to visualize and obtain kinematic data. In the end, the app generates a report with the person's spatiotemporal data, such as step length, step width, cadence, or gait speed.

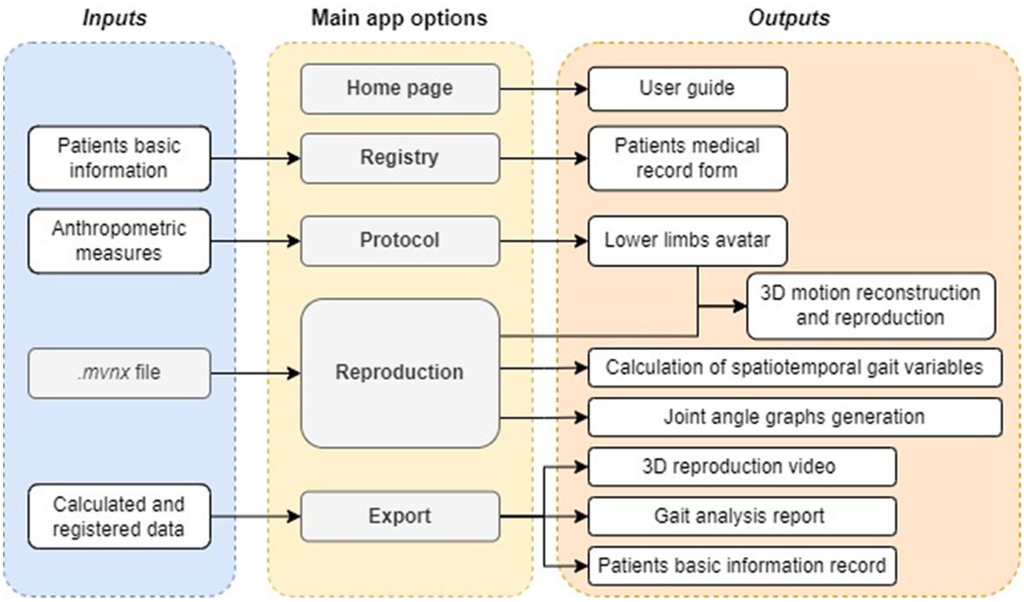


Fig. 4. ASPEBI software structure

ASPEBI GUI has a modular design whose main components are *Home Page*, *Register*, *Protocol*, *Reproduction* and *Export*, as illustrated in Figure 4.

Home page: the user first will find the *Start* page of ASPEBI GUI, where s/he has access to general information about the application, the user manual, and contact information, in case the user requires support. Likewise, the user can find the options to collect data, i.e., *Register*, *Protocol* or to process data, i.e., *Reproduction*, *Export* (see Figure 5)

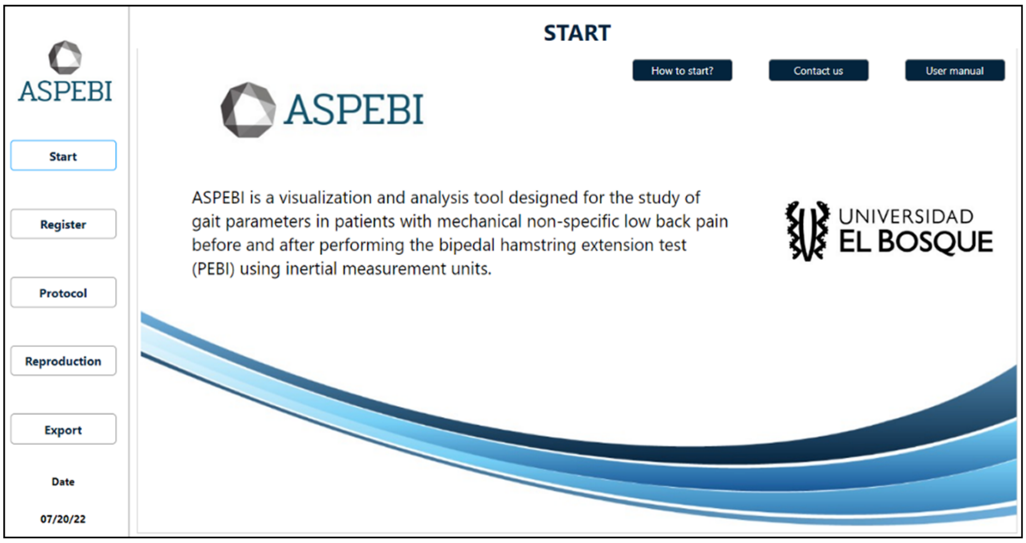


Fig. 5. Home page of ASPEBI GUI

Register: the user will find information according to his/her role. Namely, the researchers can find a panel to introduce personal and sociodemographic information about the patient. For the role of health professional, the interface was designed under the standards required in primary care by specialists, who were previously consulted to identify their needs and preferences. Accordingly, the interface of the patient's information for health professionals is based on regulations of the Ministry of Health and Social Protection [11]. Next, the user accesses the registry and selects the type of user, e.g., specialist (see Figure 6); enters the mandatory registration data and saves the patient's medical record. In case there is any error or inconsistency with the registered information, the system will automatically indicate the field and the reason for the error.

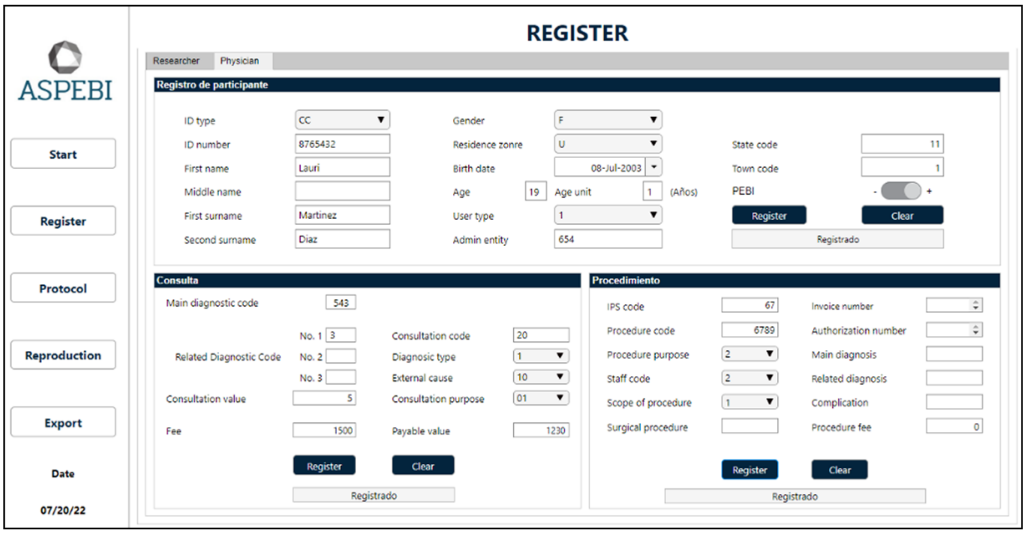


Fig. 6. Register window

Protocol: This component contains a detailed guide to carry out the protocol that includes indications about the correct manner to use the sensor units of the capture motion system including the sensors' location and the calibration system; how to measure the anthropometric data; how to properly execute the protocol mentioned in Section 2; how to generate the *.mvnx* file; and the steps to reproduce the movements generated from the *.mvnx* file. To reproduce those movements, the patient's anthropometric data are utilized to reconstruct the avatar of his/her lower limbs (see Figure 7), whose sensor locations correspond to the pelvis, thigh, leg, and foot, as illustrated in Figure 1.

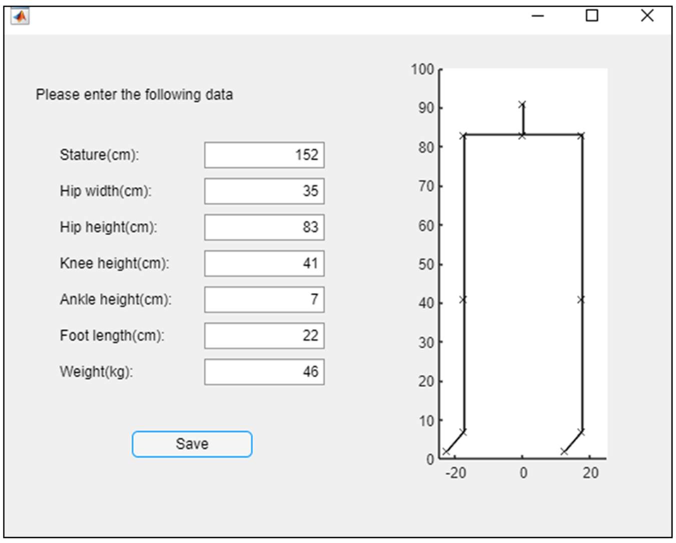


Fig. 7. Pop-up window to record anthropometric data to generate the avatar

Next, the user can click on the Protocol option, where instructions are given for each step to adequately perform the protocol, as shown in Figure 8. The user can check the step by step process to collect and save the data. The protocols that the user can perform according to the doctor's indications in primary care are shown in Figure 5. For instance, a protocol can be carried out to measure the internal and external rotation of the hip, as can be seen in Figure 9A and F; or the protocol to assess the PEBI can be conducted as indicated in Figure 9B–E.

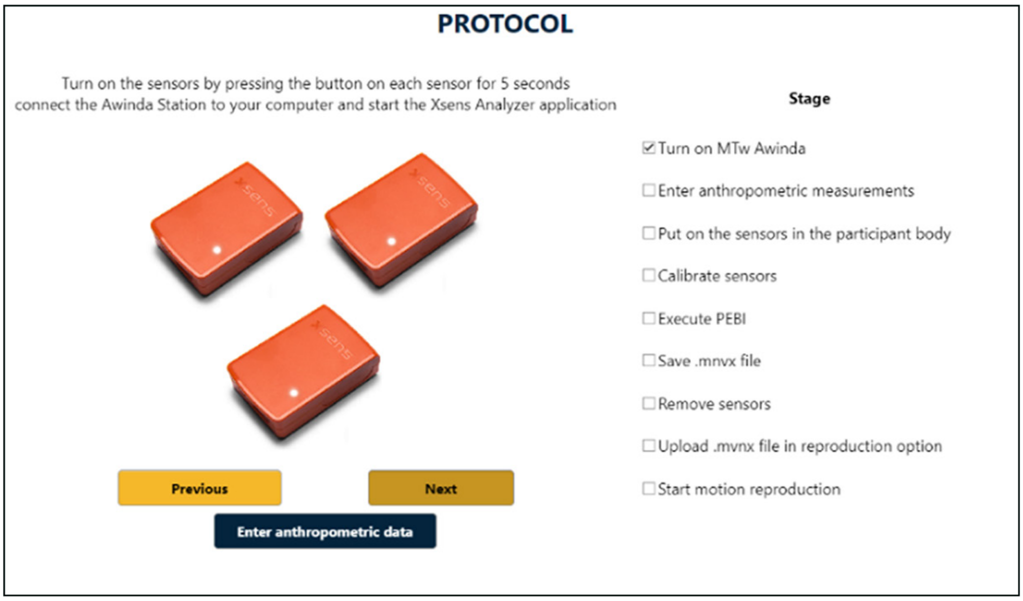


Fig. 8. Guide screen to conduct the protocol and upload the generated .mvnx file

Fig. 9. Photographic record included in the app to show the users the sequence of the protocol for PEBI

Reproduction: This component requires the *.mvnx* extension file which contains the information recorded with the MTw Awinda system. Namely, the file includes kinematic data of the body segments, such as orientation, position, acceleration, angular velocity, or joints' angles, among others. Such information allows for recreating the participant's movements through the avatar generated in the Protocol component. To this end, the preset segments of the avatar are moved in the planes of the *(X, Y, Z)* coordinate system. The reference frame has the origin *(0,0,0)* in the position of the IMU located on the left foot from which the translation of the segments is carried out on a 1:1 scale with respect to other sensors' positions; this allows us to obtain an accurate representation of the movements. As shown in Figure 10, the plot has a timeline that is synchronized with the avatar movements.

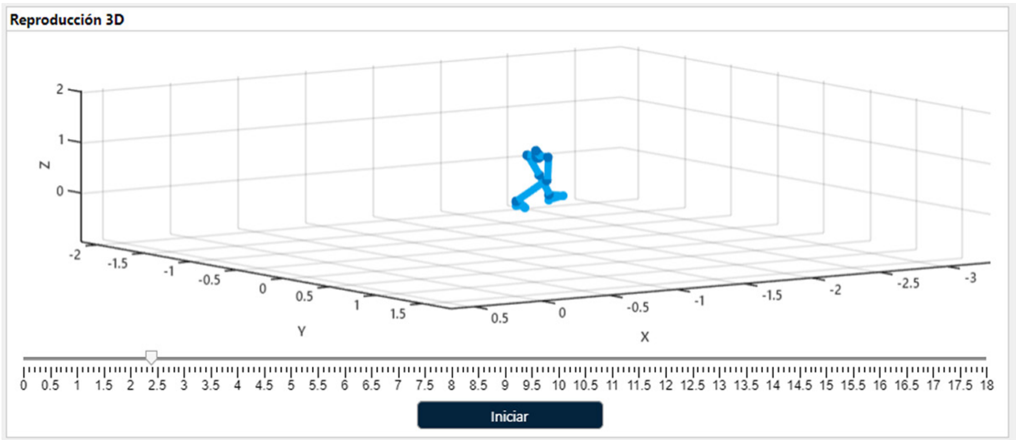


Fig. 10. 3D simulation of a patient during the PEBI performance

The panel of the kinematic variables allows visualizing the graphs of each joint of the lower limbs (see Figure 11). The joints included are hip flexion/extension, adduction/abduction, and rotation; knee flexion, extension, and rotation; and ankle dorsiflexion, plantar flexion, and rotation. The graphs of each limb for the same variable are shown in the same plot, which are differentiated by the colors red and blue; any of the joint angles can be visualized by changing the selected option.

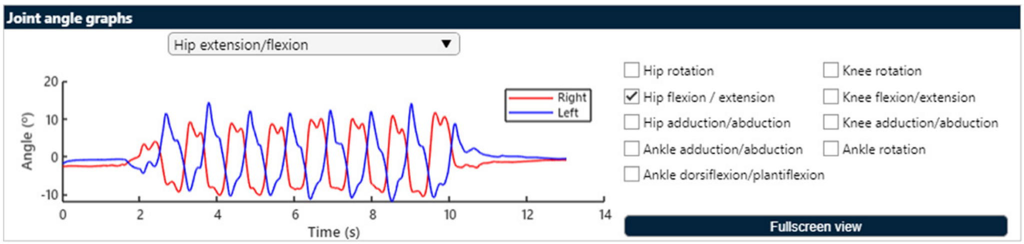


Fig. 11. Lower limb kinematic parameters panel

Export: This component allows downloading of the video of the 3D reproduction and exporting of the patient record and the report of spatiotemporal gait parameters.

5 RESULTS

In this section, we present the preliminary results of the algorithm, as well as the final window of the app in which the user can reproduce the patient movements, the spatiotemporal parameters of gait, and the joints angles of lower limbs. This information is associated with prior to post-walks to PEBI execution.

To evaluate the algorithm performance, the protocol described in Section 2 was conducted with three subjects. As mentioned, the metrics used was the mean of the error rate of each spatiotemporal parameter, as is summarized in Table 1.

Table 1. Spatiotemporal parameters errors

Parameter	Mean *e* (%)
Step Length (m)	6.63
Stride Length (m)	3.16
Step Width (m)	7.60
Gait Speed (m/s)	6.88
Cadence (step/minute)	4.27

Regarding the ASPEBI GUI, as can be seen in Figure 12, the user has access to several functionalities including the uploading of the *.mvnx* file in the *Reproduction* menu. Hence, the user can obtain the spatiotemporal parameters and the joint angles. Specifically, in the left panel are the results of the spatiotemporal parameters of the gait estimated by the algorithm described in Section 3 (see Figure 3). Likewise, the user can select which spatiotemporal parameters should be calculated, i.e., the prior or post-walk to the execution of the PEBI test, i.e., "before" or "after," respectively.

As described in the previous section, the user can reproduce the participant's movements, as well graph the joints' angles (see Section 4). A *.pdf* report can be generated which contains the spatiotemporal gait parameters and the graphs of the joint angles before and after performing the PEBI, as is illustrated in Figure 13. Likewise, the user may locally store all the information obtained including the 3D reproduction video by clicking in the *Export* option, i.e., the patient's record, the data sensors, the kinematics parameter, and the final report, which would be available anytime without dependency on the application.

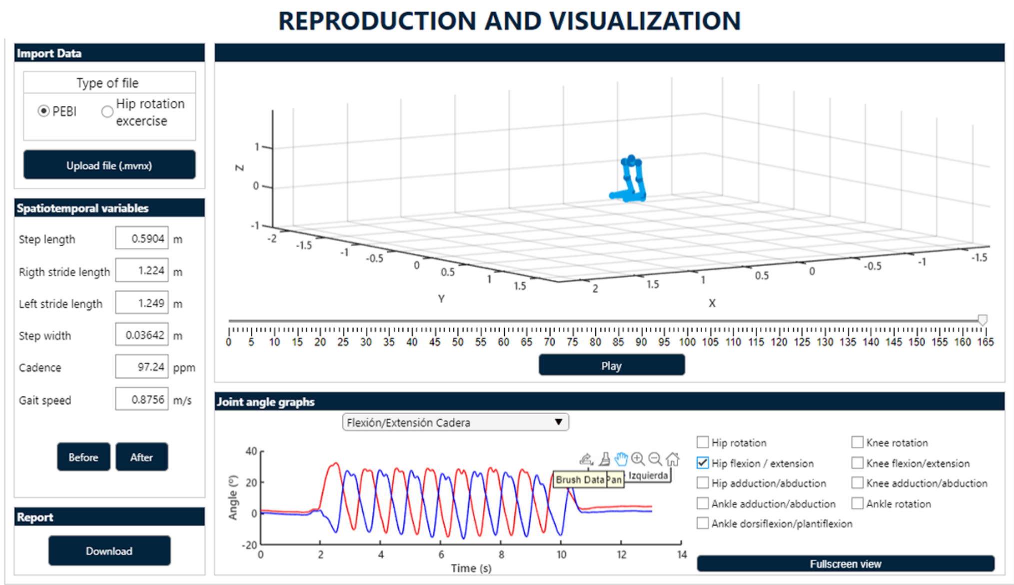


Fig. 12. Reproduction panel main functionalities

6 DISCUSSION

LBP, like other musculoskeletal conditions, is challenging to diagnose and treat. Traditional methods can be very costly and may lead to an erroneous diagnosis that can dramatically affect the patient's life. Human motion analysis is one mechanism that can provide insights into the patients' conditions; accordingly, motion capture systems have gained much attention in the last few decades. However, these systems usually are designed for general purposes and can be very costly. Moreover, since these systems are not customized for specific conditions, specialists need to look very carefully into lots of data for the information they may need to diagnose their patients. This process can be exhausting and impractical in some cases.

Bearing this in mind, in this work, we first design an algorithm that allows us to obtain the spatiotemporal parameters of gait, given that the commercial software offer such functionality but at an additional cost. In our first tests, the algorithm presented a good performance, considering that it is expected to have a high variability of spatiotemporal parameters due to the anatomical and physiological characteristics of individuals [13]. This was observed in the mean of the error rate which was less than 7.6% in all evaluated parameters (see Table 1). These preliminary results are consistent with the reported literature [14] and allowed us to appreciate the potential of the algorithms to estimate such parameters for future developments to be included in the app.

GAIT ANALYIS REPORT

ASPEBI

23-May-2022

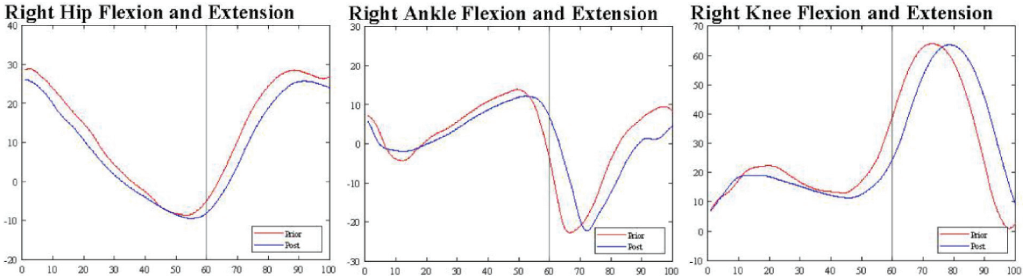
Patient general information

Name: R. S.
Sex: M
Age: 49
PEBI: Negative

Table 1. Gait spatiotemporal parameters prior and post PEBI execution

Parameter	Prior	Post	Normal values
Left Stride Length (m)	1.2343	1.186	1.007 ± 0.083
Right Stride Length (m)	1.2372	1.0937	1.07 ± 0.074
Step Length (m)	0.874	0.50201	0.545 ± 0.035
Step wide (m)	0.1148	0.0618	0.079 ± 0.013
Cadence (steps/min.)	92.3867	67.0588	128.483 ± 14.925
Gait speed (m/s)	0.80028	0.55031	1.114 ± 0.205

a)



b) **Gait Plots: Right Lower Limb Joints**

Fig. 13. Sample of a final report. a) The first part of the report, which includes information about the spatiotemporal parameters; b) The second part of the report, which contains graphs of joints' angles obtained prior (blue line) and post (red line) walks to PEBI execution

Next, the algorithm was included in the ASPEBI tool to be able to support experts in the analysis of kinematic and spatiotemporal gait parameters, thus patients with NLBP can be objectively characterized. ASPEBI is a robust and flexible application that can be used by engineering researchers and practitioners, which reinforces the use of technologies and advanced kinematic analysis tools in medical practices. This, in turn, strengthens the interdisciplinarity of low back pain research. Furthermore, the coding of the application has a modular design that allows the integration of other technologies to conduct multimodal analysis, such as electromyography. Particularly, the application provides guided assistance to collect motion information when patients execute the PEBI, which aims to assess the influence of the hamstring extension on the biomechanics of gait of patients with NLBP. Currently, the application allows users to obtain kinematic parameters and conduct gait analysis of patients from the data recorded with the Xsens MTw Awinda® motion capture system. Although ASPEBI was aimed to obtain parameters related to PEBI, it allows performing gait analysis for any purpose when a *.mvnx* file is available. Moreover, reproducing the individual's movement allows the person to observe their own movements, which can not only be motivational and enjoyable experience but also can be useful to observe, for example, if the tasks were correctly executed, or doctors and researchers can replay the movements when needed.

The app has some limitations. For instance, the algorithm requires additional testing with more subjects to include metrics associated with factors such as sex, age, or other physiological factors. The app is dependent on the data of the Xsens MTw Awinda; however, it is expected to include other options with low-cost systems based on inertial sensors. Despite these limitations, ASPEBI provides a customized solution that can provide practitioners with objective information that can process any data collected with the Xsens MTw Awinda system that are not related to the PEBI protocol. Furthermore, given that this software is user-friendly, it can be useful for conducting gait analysis in several health domains, for example, to support the study of neurodegenerative diseases [15, 16], the analysis of physical therapy results in patients with cerebral palsy [17], in the design and evaluation of prostheses and orthoses [18] and analysis in orthopedics [19, 20].

7 CONCLUSIONS

ASPEBI, a Matlab tool, was presented to support physicians and researchers in obtaining the kinematic and gait parameters of NLBP patients when they are evaluated with the PEBI clinical sign. ASPEBI extends the possibility of conducting gait analysis from data collected with the capture motion system MT Awinda of Xsens. It is a flexible application that can also be utilized and adapted to other domains that seek to integrate the knowledge of engineering and medicine when motion analysis is required. The designed modules allow the collection and processing of data in an easy-friendly manner for health professionals. In future work, due to the ASPEBI modular design, we expect to include additional modules based on other physiological measurements, such as electromyography, to improve the algorithm's testing and to process other format files to carry out biomechanical analysis of various musculoskeletal conditions.

8 ACKNOWLEDGMENTS

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