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mDurance: a Novel Mobile Health System to Support Trunk Endurance Assessment

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Abstract: Low back pain is the most prevalent musculoskeletal condition. This disorder constitutes one of the most common causes of disability worldwide, and as a result, it has a severe socioeconomic impact. Endurance tests are normally considered in low back pain rehabilitation practice to assess the muscle status. However, traditional procedures to evaluate these tests suffer from practical limitations, which potentially lead to misestimation and inaccurateness. The use of digital technologies is devised here to facilitate the task of the expert and to increase the reliability and interpretability of the endurance tests. This work presents mDurance, a novel mobile health system aimed at supporting specialists in the functional assessment of trunk endurance by using wearable and mobile devices. Concretely, a wearable inertial sensor is used to track the patient trunk posture, while portable electromiography sensors are employed to seamlessly measure the electrical activity produced by the trunk muscles. The information registered by the sensors is processed and managed by a mobile application that facilitates the expert normal routine, while reducing the impact of human errors and accelerating the analysis of the tests. A case study has been conducted in order to show the potential of the mDurance system, which results prove the interest that practitioners have in the use of a system of these characteristics.

Keywords: Mobile health; digital health; physical conditioning; physical therapy; rehabilitation; trunk endurance; wearable inertial sensors; wearable electromyography sensors; mobile devices

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1. Introduction

Conservative treatments for low back pain (LBP) are gaining popularity since there is scientific evidence of their effectiveness. According to the Global Burden of Disease 2010 Study [1], LBP is the most common cause of disability. This disorder is also ranked sixth in terms of overall burden, with a global point prevalence of 9.4%. Furthermore, a recent study [2] has highlighted that the prevalence in the adult general population is approximately 12%, with a one-month prevalence of 23%, a one-year prevalence of 38%, and a lifetime prevalence of more than 40%. Likewise, it is also noteworthy the prevalence of LBP among adolescents, which is about 30% [3]. LBP has an enormous social and economic impact [4], and is a leading cause of absenteeism in all professions [5]. The growing interest of the scientific community in the study of LPB is also reflected by recent studies [6–8].

Pathophysiologically, LBP is associated to a wrong lumbar-pelvic stability [9]. General exercises for the whole body and encouragement of the individual to stay active have been shown to be beneficial for preventing and dealing with chronic LBP [10]. However, in recent years, a major emphasis has been put on the provision of more specifically directed exercises, which are aimed at targeting the muscles involved in low back stabilization. By this means, more effective and efficient exercise programs can be developed. In order to establish goals, monitor progress towards those goals, and guide the prescription of specific exercises, a functional assessment of the trunk stabilization or endurance turns to be utterly necessary [11]. Trunk muscle endurance assessment, normally referred as to trunk endurance assessment, consists in the evaluation of the muscular capacity of an individual's trunk. To determine the resistance of the trunk muscles, experts traditionally measure and annotate the observed time a patient can hold a given posture part of a test. Nevertheless, this form of evaluation is subject to potential errors, mainly posed by the subjectivity associated to the estimation of the test finalization and the effective measurement of the time elapsed during its execution [12].

Digital technologies can serve to cope with some of the limitations introduced by human errors during the practice of medical procedures. In fact, during the last years, the use of devices and software in healthcare disciplines has become more common due to the constant technological improvement [5,13,14]. There are different factors attributable to the development of this type of systems: the demand by health care users for novel forms of treatment [15]; the globalization of health systems [16]; the need of reduction of health care costs [17]; and the major advances in information and communication technologies [18]. Telehealth, eHealth, Social Health, and Health IT are some of the most prominent areas in which telecommunications and computer technologies are combined to expedite and enhance healthcare procedures. Currently, at the forefront of the digital health revolution is the so-called mobile health (mHealth) [19], which refers to the practice of medicine and public health supported by mobile devices and applications. The interest in this domain has been particularly boomed by the growth of wearable and mobile technologies [20], as well as the intensive effort put by research institutions and companies in the development of systems [21,22] and platforms [23–26].

In the light of present challenges of physical rehabilitation and conditioning routines as well as the potential of mHealth technologies, this work presents mDurance, a mobile health system intended to support experts in the functional assessment of trunk endurance by using wearable and mobile devices. The system has been defined to overcome some of the most relevant limitations faced by specialists during the course of endurance tests, such as the determination of the patient's initial posture, the estimation of the duration of the test, and the measurement of the muscle fatigue. The mDurance system leverages the use of wearable inertial sensors to track the patient trunk posture, and portable electromiography sensors to seamlessly measure the electrical activity produced by the trunk muscles. All the information registered through these sensors is intelligently managed by a mobile application that facilitates the expert normal routine, helps mitigate human errors and accelerates the analysis of the tests. The rest of the paper is structured as follows. Section 2 presents an overview of the state-of-the-art in mobile health applications for LBP. The fundamental principles of the trunk endurance assessment and most common tests are outlined in Section 3. The proposed mDurance system is described in Section 4. A preliminary case study is presented in Section 5, while final conclusions and remarks are summarized in Section 6.

2. Related Work

According to a survey performed in UK [27], the use of medical apps is of 72.4% among doctors, and as high as 83.3% among medical students. The majority of both students and doctors owned from 1 to 5 apps, which they used on a regular basis. Moreover, this study highlights that the most frequently used apps are devoted to detail medication references as well as disease diagnosis and management. In relation to these findings, it is fairly justified the continuous development of medical apps focused on clinical aspects. In fact, the high level of smartphone ownership and the more intuitive and user-friendly applications are compelling reasons suggesting that medical apps will offer a real opportunity to impact on the efficiency of working practices and patient care. The market of medical applications is primarily led by Apple's iOS platform [28]; however, its use is tailored to a reduced and expensive catalog of devices. Alternatively, Android provides its users with a wider variety of systems of different prices and vendors at the reach of a broader audience, which is increasing its competitiveness in this domain [29,30].

In our society, the utilization of the Internet to seek medical information has unarguably increased during the recent years. The analysis of the searches done over the Internet helps better understand the interest of people in medical tools and illnesses. Concretely, Figure 1 depicts the worldwide trends with respect to the search of "Low Back Pain" and "Medical App" concepts. LBP shows a sustained popularity in people searches over the last seven years, which might be related to the high prevalence of this disease and the necessity of information regarding symptoms and potential treatments for this condition. With respect to medical applications, it is clear from the trends that people are growingly

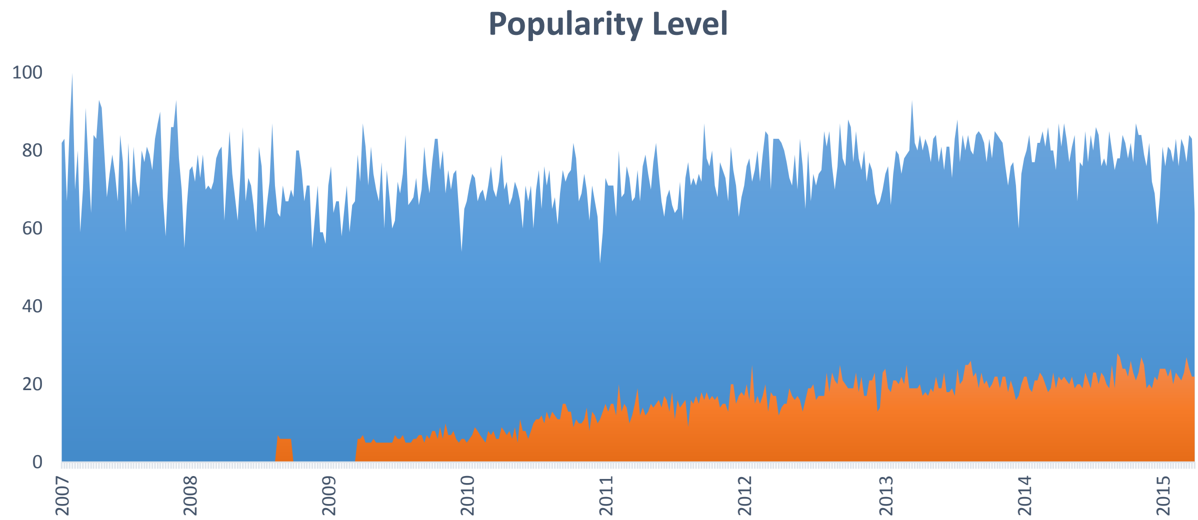

Figure 1. Interest over time in "Low Back Pain" (blue chart) and "Medical App" (orange chart) terms. Results obtained through *Google Trends*. The values, expressed in percentage, reflect the amount of searches that have been done for each term, relative to the total number of searches done on Google over time.

interested in this sort of technology. It should be taken into account that these trends only refer to searches in English; thus, if other languages are considered, the popularity level could likely increase.

Having a look at the main application catalogs, i.e., Google Play and Apple Store, several apps can be found in relation to LBP. The vast majority of apps are planned to promote exercises to prevent or relief LBP. Also, apps with informative or academic purposes and others focused on diagnosis are available. The number of apps to help alleviate LBP symptoms is especially elevated. Some examples are *Stretch Away* [31], *Back Doctor* [32], *iREHAB* [33], *Prevent Back Pain* [34], *Yoga for Back Pain Relief* [35], *WebMD Pain Coach* [36] and *Upper & Lower Back Pain Relief* [37]. The operation of these applications is mainly oriented to provide trunk exercise recommendations. They fundamentally consist of a database of image or video exercises, which are used to guide the patient or person suffering from LBP on how to execute them. This category of apps is available for any sort of users, and normally, they do not take into account the potential diseases that may lead to LBP. The group of apps focused on providing patient or professional-oriented LBP information is also considerable. Some examples within this domain are *Back Pain Guide* [38], *Back Pain Complete Guide* [39], *Back Pain: An Algorithmic Approach to Low Back Pain* [40], *Back Pain Causes And Cures* [41] and *Back Pain Nerve Chart* [42]. This group of apps only offer information regarding the essentials of LBP, including causes, treatments or even descriptions of the back anatomy. Lastly, the group of apps dedicated to support diagnosis of habits or postures that can lead to LBP constitutes the less relevant at the moment in the marketplace. Some examples related to this group are *PostureScreen Mobile* [43], *Clinical Pattern Recognition: Low Back Pain* [44] and *Virtual Diagnosis Spine* [45]. The main purpose of these apps is to recognize LBP through requesting the users to provide information related to different LBP symptoms. Some of them also help customers identify different posture alterations.

A comprehensive search has been performed to find specific applications and systems to evaluate trunk endurance using traditional tests. However, no relevant results have been obtained. In view of the search result, it seems that there is a clear opportunity for the development of applications and systems that may help specialists perform trunk endurance assessment.

3. Trunk Endurance Assessment

Different tests are available to assess the trunk endurance in people with or without LBP. These kind of tests are performed by a specialist, and they normally consist in the measurement of the time a person can hold a specific posture involving the trunk muscles. During the execution of the test, the health professional has to control the patient position and decide when the test ends, according to some established termination criteria. The results obtained for a given patient help experts determine their status and muscular capacity, as well as their ability to hold a posture normally related to daily living activities.

To assess the low back stabilization several functional trunk endurance tests can be found in the literature [11,46]. The most widely used ones are the *static trunk extensor endurance test* (STEET), also known as Sorensen test [47], the *trunk curl static endurance test* (TCSET), also known as trunk flexor endurance test [48], and the *side bridge endurance test* (SBET) [12]. In the STEET, the subject has to maintain a horizontal unsupported posture with the upper body extending beyond the edge of the bench. In the TCSET, a curled position must be hold with only the scapulae clearing the table. Finally, the SBET requires the individual to lie on their side while lifting the torso and thigh off the bench, such that the body weight is on the elbow and feet. Special remarks are that two chances are given to the individual to execute the STEET, while evaluation of both left and right sides are considered as part of the SBET. A detailed description of each test, including posture, procedure and finalization criteria, is shown in Table 1.

The average endurance time for STEET is established from 62 to 131s. In TCSET the mean duration for young, healthy men and women is 134s, while for the SBET it boils down to approximately 84s, with an standard deviation of 24.5s. Not only the independent duration of each test is of relevance for the trunk endurance assessment, but also the relation among these values. Hence, ratios between flexor/extensor muscles and right/left sides are normally considered. These ratios show the equilibrium or disequilibrium between muscle groups. The ratio of trunk flexor to extensor endurance is 0.77 normally (0.84 in young males and 0.72 in young females). The ratio of right side bridge to left side bridge endurance is normally 0.96. A reduced ratio of trunk flexor to extensor help discriminate between LBP patients and healthy individuals, while a side to side difference greater than 0.05 suggests unbalanced endurance. The estimation of these reference values is explained in [11].

During the course of the realization and evaluation of these tests, practical limitations can be observed. First of all, it is widely accepted that the tester has an important responsibility while determining the different phases of the test. The estimation of the beginning and end of the tests is completely subject to the expert visual interpretation. In fact, specialists often report on the difficulties faced during the observation of the trunk angle variation, as well as the consistency of these measurements among sessions. This makes complex the comparison of values measured by different testers. Moreover, during the test, the expert needs to control several aspects simultaneously, such as, time, position, and possible abnormalities, which in traditional procedures are sometimes despised. Finally, the results are mainly

Table 1. Trunk endurance tests description.

	Static trunk extensor endurance test (STEET)	**Trunk curl static endurance test (TCSET)**	**Side bridge endurance test (SBET)**
Patient position	- Prone with the inguinal region/anterior superior iliac spine at the edge of the bench.	- Arms are folded across chest and back laid on a piece of wood to support the patient at a fixed angle of 60°.	- The subject lies on one side supported by their pelvis, lower extremity and forearm.
	- Arms at sides, ankles fixed (by strap or hands), holding horizontal position.	- Toes are anchored either with a strap or by the tester.	- The top leg is placed in front of the lower leg with both feet on the floor.
		- Both knees and hips are flexed 90°.	- The upper arm is placed against the chest with the hand touching the anterior lower shoulder.
Procedure	- The patient maintains the horizontal position as long as possible.	- The wood is pulled back 10 cm (4 in.).	- The pelvis is raised off the table as high as possible and held in a line with the long axis of the body, supporting the weight between the feet and elbow.
	- Timing begins when posture is horizontal and unsupported.	- Timing starts when the initial posture is achieved.	- Timing starts when the initial posture is achieved.
	- Subjects are verbally encouraged to hold this position as long as possible.	- The subject holds the isometric posture as long as possible.	- Subject statically maintains this elevated position.
Termination Criteria	- The position is held up to a maximum of 240s.	- No specific time limitation although generally considered a maximum of 240s.	- No specific time limitation although generally considered a maximum of 240s.
	- If patient drops below the horizontal position more than 10° (an additional chance to regain it is given after first attempt).	- When any part of the subject's back touches the wood. This generally equals to a drop of more than 30° with respect to the reference.	- Subject is unable to lift their body up from the floor or drops their pelvis or thigh part way more than 10° and cannot raise it up to the start position again.
	- If patient reports LBP or cramping in their legs the test may be stopped.	- Significant LBP causes the test to be stopped.	- Significant LBP causes the test to be stopped.

elaborated on the time recorded during the performance of the test, and that is the unique information to compare with in future tests. This relates to the common impossibility of quantifying the relative muscle strength developed by the individual. A detailed description of these limitations can be found in [49,50].

4. mDurance: A Novel System for Trunk Endurance Assessment

Taking into account the limitations of traditional approaches, this work presents *mDurance*, an innovative system to support practitioners during regular trunk endurance assessment procedures. The mDurance system combines wearable sensors, capable of measuring physiological and biomechanical data, and mobile devices, dealing with the gathering, processing and persistence of the sensory data as well as the visualization of health outcomes. Concretely, the system consists of a wearable inertial sensor to estimate the trunk position and an attachable electromiography sensor to measure the activity of the skeletal muscles of the trunk. All the information generated by the sensors during the execution of the endurance tests is seamlessly transmitted to a mobile application, which develops on some of the functionalities provided by a recent mobile health framework [51]. The key features of the mDurance system are thoroughly described next.

4.1. Automatic Measurement of Trunk Posture

Determining the human trunk posture is of crucial importance to set the start of the endurance test as well as to automate the identification of its completion. To do so, mDurance benefits from the use of an inertial measurement unit (IMU), which combines triaxial accelerometers, gyroscopes, and magnetometers, enabling the measurement of the absolute attitudes or inclinations of the body part the sensor is fastened to. This technology, extensively used in the navigation domain [52], has been exploited during the recent years for body movement analysis [53–57]. Apart from their precision, these sensors are particularly interesting since they are completely self-contained, thus introducing constrains neither in motion nor any specific environment.

IMUs provide raw acceleration, angular rate and magnetic field data that need to be fused together to obtain a sole, optimal estimate of orientation. Diverse algorithms have been proposed in the literature to that end, including Kalman filters [58], Least Squares filters [59] or Gaussian Particle filters [60], among many others [61,62]. The mDurance system particularly implements a recent technique, the Madgwick's algorithm [63], which outperforms most existing approaches in terms of implementation complexity, sampling rate requirements and computational needs. This technique does not suffer from well-known limitations of other solutions, like the singularity problem associated with the Euler angle representation (gimbal lock). Besides, this method also omits the use of computational expensive trigonometric functions, making it more efficient and easier to implement for real-time purposes. Madgwick's algorithm employs acceleration, angular rate and magnetic field measurements to analytically derive, through an optimized gradient-descent method, a quaternion representation of motion [64]. Thus, the output of the algorithm is a quaternion, a compact vector in the form (q_1, q_2, q_3, q_4), which dynamically represents the orientation of the sensor. A detailed description of the foundations of the considered algorithm can be seen in [65].

Quaternions are frequently used in orientation estimation algorithms because of their numerical stability and computational efficiency. However, this representation is difficult to interpret and visualize since it defines a $\mathbb{R}^4$ space that cannot be represented in a human-understandable three-dimensional view. Accordingly, a translation into Euler angles is performed here, after all the calculations to estimate the quaternion are carried out. Euler angles represent the possible rotations around the three cardinal axes, namely, yaw (φ), for the X axis, pitch (θ), for the Y axis, and roll (ϕ), for the Z axis. Given the estimated quaternion, the Euler angles can be simply obtained as follows:

$$\varphi = arctan\left(\frac{2(q_1q_4 - q_2q_3)}{1 - 2(q_1^2 + q_2^2)}\right) \tag{1}$$

$$\theta = arcsin\left(2(q_1q_3 - q_4q_1)\right) \tag{2}$$

$$\phi = arctan\left(\frac{2(q_1q_2 - q_3q_4)}{1 - 2(q_2^2 + q_3^2)}\right) \tag{3}$$

4.2. Automatic Estimation of Muscle Fatigue

During the execution of the endurance tests, the muscles are normally subject to an important level of activity and stress. Having a continuous description of the evolution of this activity is of much clinical relevance to determine the muscle fatigue and potential physiological abnormalities [66]. As a consequence, mDurance incorporates a means to seamlessly monitor the electrical activity produced by the skeletal muscles. To that end, a wearable electromyography or EMG sensor is used. This sensor consists of a set of surface electrodes, which are attached to the skin of the body part to be monitored. The electrodes measure the potential difference between the electrodes, which is translated by the sensor into EMG signals. Experts usually focus on the analysis of the shape, size, and frequency of the resulting electrical signals. However, there exist some well-known metrics that help categorize the level of the muscle fatigue. The root mean square (RMS), the average rectified value (ARV), and the maximum voluntary muscle contraction (MVC) are generally used as indices of muscle fatigue [67,68]. This information is of much interest to compare the evolution of the muscle strength among sessions, as well as to measure the effectiveness of potential treatments. Given the EMG signal, and a time window or epoch of N samples, the RMS, ARV and MVC values can be calculated as follows:

$$RMS = \sqrt{\frac{\sum_{k=1}^{N} EMG^2(k)}{N}} \tag{4}$$

$$ARV = \frac{\sum_{k=1}^{N} |EMG(k)|}{N} \tag{5}$$

$$MVC = max\left(EMG(k)\right) \tag{6}$$

4.3. Sensor Setup and Application Description

One of the main aims of the mDurance system is to help experts assess, in a precise manner, the time invested by the patients during the execution of the trunk endurance test, as well as the amount of muscle fatigue experienced in that process. To attain the first objective, an IMU sensor is considered to determine when the test finalization criteria is met, based on the principle presented in Section 4.1. For the second goal, an EMG sensor is used to continuously detect the electrical potential generated by the muscle cells in the course of the test, as explained in Section 4.2. Shimmer wearable sensors, concretely, version 2 for the EMG and version 3 for the IMU are employed, given the high reliability yielded by these commercial devices [69]. The default sampling rate configuration, i.e., 51.2Hz, is used for both sensors since it proves to be enough for an accurate estimation of the trunk angle and EMG metrics.

Figure 2 shows the sensor deployment for each of the three trunk endurance tests supported by mDurance and described in Section 3. The sensors are located in convenient positions to ensure stability and comfortability, as well as an accurate measurement of both trunk angles and EMG values for each test. In the STEET and TCSET, the trunk angle is measured with respect to the coronal plane, while for the SBET the reference corresponds to the sagital plane. Accordingly, the IMU sensor is attached to the lumbar zone (D12-L1 vertebra) for the STEET and TCSET procedures, and to the dorsal for the SBET. Taking into account the placement of the IMU sensor for each case, and its local frame of reference orientation, the roll angle (ϕ) is used to represent the trunk angle in all tests. The EMG sensor is placed on the lumbar (erector spinae), abdominal (rectus abdominis) and external oblique parts for the STEET, TCSET, and SBET, respectively. The electrodes are distributed to cover a sufficient muscle area.

In the following the mDurance application is described (Figure 3). For the first time use, the expert is requested to sign up with their personal information to register in the system. This information is used by mDurance to uniquely identify the specialist, and also preserve the patient's data collected by the system. Once an expert profile is created, the practitioner can log into the application contents by using their username and password (Figure 3(a)). Then, the expert is directed to a new screen, in which they can either select one of the existing patients in the system database or include a new one (Figure 3(b)). Personal information, such as name, age, height, weight, gender, and possible health conditions, are requested when filling a new patient registry. Thereupon selecting a patient, their more relevant personal information is presented to the expert for quick inspection, including the date of the last endurance session and particular conditions they suffer from. Moreover, from this main screen the expert can either initiate the connection with the wearable sensors, start the endurance tests or visualize the historical data collected during previous sessions.

The connection with the wearable sensors is performed by clicking on "Connection" (Figure 3(b)). During the very first configuration of the system, the sensors must be paired with the mobile device. To do so, the Bluetooth interface is activated, and both the mobile device and the Shimmer sensors bound. After configuration, this one-time process is no longer required, unless the sensors are replaced. From then on, the expert can normally trigger the connection of the mobile and the wearable devices by pressing the power button (Figure 3(c)).

Once the sensors are connected, and in order to proceed with the execution of the tests, the expert has to press "Start Tests" (Figure 3(b)). As a result, the specialist is directed to a new window in which the particular test to be performed can be chosen (Figure 3(d)). After selecting a test, another screen is displayed with the essential elements required by the expert to perform the test (Figure 3(e)). This includes a graph to visualize the recorded EMG signal at runtime; a timer to control the time left according to the maximum duration allowed for the realization of the test; and the trunk angle continuously measured by the system. The trunk angle is particularly useful for the expert to determine when the patient is correctly positioned. Then, once the specialist determines that the starting position is reached, the test can be initiated by clicking on the corresponding button. The angle measured at that moment is saved as a reference, and used by the system to check whether the user exceeds the range defined for each test as part of the termination criteria. Thus, if the patient relaxes their posture more

(**a**)

(**b**)

(**c**)

Figure 2. Sensor deployment for (**a**) STEET, (**b**) TCSET and (**c**) SBET procedures.

than $\pm 10°$ in the STEET and SBET, or $\pm 30°$ in the TCSET, the test is automatically finished. The end-of-test is also attained when it lasts more than 240s or when the expert explicitly considers that it should be finalized, for which the stop button can be used. After the test is concluded, the expert can observe a summary of the results obtained for the performed evaluation (Figure 3(f)). This includes the total duration of the test (sum of the two attempts for the STEET case), the endurance ratio, and the RMS, ARV and MVC values. Also, the session is categorized into "bad", "good" and "perfect" based on the statistical overall duration of the patient, introduced in Section 3. Concretely, the ranges are bad=$[0, 61s]$, good=$[62, 131s]$ and perfect=$[132, 240s]$ for STEET; bad=$[0, 133s]$, good=$[132, 240s]$ for TCSET; and bad=$[0, 60s]$, good=$[61, 108s]$ and perfect=$[109, 240s]$ for SBET.

Figure 3. mDurance application snapshots: (**a**) Login; (**b**) Patient selection; (**c**) Sensor connection; (**d**) Endurance test selection; (**e**) Test execution; (**f**) Test results summary; (**g**) Selection of historical attributes to be represented (part of); and (**h**) Historical representation.

Finally, the expert can inspect the patient's historical data by clicking on the "Historical" button (Figure 3(b)). This opens a new screen (Figure 3(g)), in which diverse type of representations can be selected, such as the time invested by the patient during the execution of the test and the muscle fatigue metrics. The results are depicted in a multidate basis for the different past sessions registered in the system for the specific individual (Figure 3(h)).

4.4. App Implementation

mDurance has been implemented using mHealthDroid [51], an open source framework devised to support the agile and easy development of mHealth applications on Android. mHealthDroid, which is released under the GNU General Public License version 3 and available at [70], provides resource and communication abstraction, biomedical data acquisition, health knowledge extraction, persistent data storage, adaptive visualization, system management and value-added services. mHealthDroid has considerably facilitated the implementation of the mDurance core functionalities, such as the interface to the wearable sensors, the calculation of the test results, the persistent data storage, and the visualization of the collected sensor information and historical test results.

The mDurance communication functionality relies on the mHealthDroid Communication Manager, which abstracts the underlying mobile and biomedical devices, makes the communication transparent to the application, and provides a unified and interpretable data format. Concretely, the mHealthDroid Adapters for Shimmer2 and Shimmer3 wearable devices are used to communicate these devices with the mobile phone and to map their data to the proprietary format. mDurance performs a Bluetooth scan to detect available wearable devices and pairs them with the mobile phone. This functionality is implemented by using the mHealthDroid System Manager, which builds on the standard Android API [71].

One of the key features of mDurance is the estimation of the roll angle utilized to detect the trunk postures, the computation of the different endurance test times, and the calculation of the RMS, ARV and MVC values based on the EMG signals. This functionality develops on the mHealthDroid Data Processing Manager, which implements off-the-shelf signal processing techniques and data mining methods.

The sensory data collected during the endurance tests, the test results calculated by the mDurance core functionality, as well as the patient profile information are stored on a local database. The expert can register patients in the User database including their name, age, gender and contact information and update the personal information. The angle values and EMG collected during the endurance tests are buffered and periodically stored on the Sensor table, in order to ensure efficiency. Once the test is completed and the results are calculated, these are persisted on the User table. The mDurance storage functionality builds on top of the mHealthDroid Storage Manager, which provides a high level of abstraction from the underlying storage technology and enables data persistence both locally and remotely. In the current implementation, the mDurance app stores data locally on a SQLite database [72] deployed on the mobile phone SD card. However, the mHealthDroid Storage Manager also provides remote storage capabilities which could enable the easy extension of the current mDurance application to store data on the cloud.

mDurance provides graphical representation of online EMG values collected from the wearable device, as well as of the historical endurance test results, for example, the test times and the calculated muscular fatigue values. Two types of graphical visualization are implemented using the mHealthDroid Visualization Manager, which supports diverse modes and ways to display data and builds on the open source library Graphview [73]. On the one hand, the data collected by the wearable EMG sensor and provided by the mHealthDroid Communication Manager is depicted on a line chart in an online fashion. On the other hand, the processed endurance test results, which are stored on the permanent storage and provided by the mHealthDroid Storage Manager, are represented on a bar diagram in an offline operation manner.

5. Evaluation

The proposed mDurance system has been designed taking into account some of the most important limitations faced by practitioners during the course of traditional trunk endurance assessment tests. Thus, in order to show the potential of this system, a preliminary analysis of its use has been performed. To that end, ten volunteers, eight males and two females ranging from 21 to 37 years old, were recruited to be evaluated by three external physical therapists using both mDurance and traditional procedures. The procedures were executed sequentially since a simultaneous evaluation cannot be performed. The reason is that the instructions given by the tester based on visual inspection, for example, finalize the first attempt and start the second chance in STEET, can influence the normal flow of the decisions made through mDurance and vice versa. To procure the reproducibility of the tests, a rest time of more than one hour was considered to ensure the full recovery of the subjects in between the execution of both procedures. The tests were explained to the subjects before performing the sessions, assuring the full understanding of their phases. Traditional sessions were performed as detailed in Section 3, while for those involving the mDurance system the tests were carried out as described in Section 4. Accordingly, the execution was similar from the subject perspective, but the expert had to visually determine the start and end of each test and also use a stopwatch to time it for the traditional approach, while in the use of mDurance these processes were automated.

After the realization of the tests, the three experts were asked to provide their impressions regarding the use of mDurance. First, they noted the practicality of the automatic angle measurement for initiating and finalizing the tests. In fact, they commented that the position adopted by the subjects through following the app guidance seemed to be more adequate than the one based on instructions from visual inspection. For example, in the TCSET a wedge is used to fix the initial position to an inclination of 60°, and then this wood is pulled back ten centimeters before starting the test. During the process of pulling back the wedge, individuals tend to relax the posture and bend the trunk more than required; this occurs while the expert is operating the wood, thus the initial reference is usually not conserved. Conversely, specialists experienced more reliability when using mDurance, since they could just initiate the test whenever the appropriate angle was reached by the subject as shown in the app. Likewise, the experts were truly impressed with the precision of the estimated angle and agreed that the finalization time was fairly determined. Furthermore, the real-time EMG representation was greatly appreciated, especially to observe the muscle contraction during the realization of the test. This feature, together with the calculation of RMS, ARV and MVC values, were considered important assets of the system. The experts commented on the interest of having an automated log of time and muscle fatigue values to evaluate the patient improvement during their treatments or preventive interventions. In fact, they appreciated the fact that all the information is automatically persisted into the system, and it can be retrieved and displayed at any time, even the data from prior sessions. They also considered this of much relevance for potentially constructing an evidence training program. Finally, the simplicity in the app usage and friendliness of its interface were highlighted as well. Indeed, this was considered during the development of the application, which seeks to attain ease of use and intuitiveness without sacrificing functionality.

Table 2. Case study results. BMI values are expressed in kg/m^2 and test duration in s.

Patient ID	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Age	28	27	34	31	28	37	28	23	26	21
BMI	27.03	23.24	23.91	21.23	21.91	29.94	23.87	22.79	28.63	30.20
STEET (T)	43	56	59	121	104	48	98	123	59	75
STEET (mD)	32	59	108	123	99	60	105	117	52	85
TCSET (T)	42	79	107	112	101	79	118	78	77	154
TCSET (mD)	66	74	148	99	89	59	94	79	71	144
SBET right (T)	30	31	51	38	33	34	52	55	21	39
SBET right (mD)	25	20	69	44	38	36	52	46	17	62
SBET left (T)	26	28	54	46	35	30	35	46	28	25
SBET left (mD)	29	30	72	52	32	34	39	45	18	55

(T) Traditional method.
(mD) mDurance method.

Although experts did not report special negative comments, they mentioned that simpler guidelines should be provided along with the mDurance application to accelerate the understanding and usability of the whole system. During the first interaction with mDurance they faced some troubles when connecting the sensors, which were nevertheless overcome after following the instructions given by the designers. Furthermore, they considered desirable to share the data among diverse platforms, since the current version of the system limits its use to a single device. All these valuable comments have been especially taken into account for future extension of this work.

Apart from the expert experience, the aim of this evaluation was also to compare the results of the tests by using both approaches. As commented above, a strict comparison of both procedures is not possible since any kind of intervention during the course of the test would impact the results of the opposite approach. Despite this fact, it is well-accepted in the physical therapy domain that endurance test results tend to replicate, provided that the subject rests sufficiently in between tests and when these are performed in similar conditions. These considerations fit in well with the experimental settings of this case study. The results of the experiment, i.e., time measured for each individual, test and procedure, are shown in Table 2. As it can be observed, the results obtained through both methods are generally in line, which reflects the utility of the developed system. Significant differences are nevertheless observed for some cases. These variations would be likely observed even if the measurements were performed through two independent rounds of traditional assessment tests. In fact, multiple factors such as the subject awareness, concentration or the environment itself can influence the normal execution of the test. Though these results show promising, a study including a higher number of subjects would be required to further confirm these findings. Finally, it is worth noting that the data collected through this kind of experiments could be used for clinical analysis out of the scope of this work, such as exploring the relationship among diverse physiopathological factors or lifestyle conducts leading to LBP.

6. Conclusion

A spectacular proliferation of medical applications and systems has been observed during the recent years; however, more significant contributions are still necessary to simplify, expedite and improve traditional health practices. In pathophysiology, trunk endurance assessment is a clear application area lacking of appropriate tools. In fact, experts normally suffer from diverse kind of limitations during the use of traditional procedures, such as difficulties in the precise estimation of the duration of the test, challenges in the evaluation of the muscle strength, and other sort of problems related to the subjective nature of each specialist assessment. Moreover, practitioners need to concentrate on measurement and annotation tasks instead of focusing on most relevant duties during the course of the test, like the analysis of the individual's behavior. To overcome these limitations this work has presented mDurance, an innovative system that combines wearable inertial and electromyography sensors together with mobile devices for supporting a more accurate and rapid assessment of trunk endurance. The inertial sensors are used to continuously obtain the attitude of the trunk based on quaternions theory. This absolute trunk orientation helps experts determine when the user attains the correct posture to initiate the endurance test, as well as to automatically identify its finalization based on established termination criteria. The electromiography sensor allows practitioners to observe the trunk muscles activity during the execution of the tests, as well as the level of muscle fatigue experienced by the subject. All the information is processed by a mobile application that develops on a novel mHealth framework. The app significantly simplifies the routine of the expert and helps manage the information collected from multiple individuals and sessions, which is considered of primal interest for tracking the evolution of the patients from visit to visit. An initial evaluation of the mDurance system has been performed to showcase the potential use of this system. Taking into account the high level of satisfaction shown by experts, next steps include the use of mDurance on a large scale clinical test bed, which is currently under development.

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Author Contributions

O.B. and J.A.M.M. are the principal researchers of this study and main authors of this work. M.A. has identified the physical models. N.D. has implemented the mDurance application and collected the experimental data together with J.A.M.M. O.B., J.A.M.M. and C.V. have written the paper. M.A., M.D., E.H.V, C.S.H., S.L., H.P. and I.R. reviewed the manuscript for scientific content. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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