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Patients' evaluation based on digital motion acquisition

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ABSTRACT
The paper explores the possibility of using low-cost motion capture technologies to automatically evaluate patient's condition concerning his/her walking condition. Two different technologies, optical markerless and inertial, are used to track the gait to be adopted in a doctor's office or at patient's home. The data acquired are elaborated using commercial and in-house developed tools with the aim of creating, in a near future, a simple environment for medical staff and people non highly skilled in IC technology. The paper shows the feasibility of an automatic detection of a set of gait abnormalities affecting people having a lower limb prosthesis. This constitutes a robust support for orthopedic technicians work and foresees the use of such technology for larger surveys and early detection of gait deviations.

KEYWORDS
Motion Capture; Gait Analysis; RGB-D sensors; Inertial sensors

1. Introduction

The development of mobile health systems has inspired a patient-centric approach to measure and monitor health metrics. The use of portable and wireless devices impacts on health outcomes, services and research [2]. Sensors can be used to track basic parameters such as blood pressure, heart rate and body temperature but with the advent of motion capture sensors, also mobility, gait and the frequency, intensity and duration of physical activity can be measured, stored or transmitted.

The emerging technologies pulled by the video gaming industry open a wide range of opportunities. New ways can be used to assess the performance and the level of disability or function in a patient after an adverse health event. Rehabilitative or disease progress as well as therapeutic impact can be assessed in a quantitative and ubiquitous mode. Different monitoring systems can be used by technicians in rehabilitation centers and hospitals or by patients themselves at home in everyday life.

Within this context, the paper shows a novel approach aimed at increasing automatization in acquiring and using patient's data referring to mobility so that the whole process requires human intervention only for the decisional steps. An application will be shown in the analysis of gait for people with a lower limb external prosthesis by means of optical and inertial motion capture sensors.

2. Background

Literature shows a number of applications of high tech sensors to monitor health metrics. The most diffused are used to control acute or chronic conditions mainly due to cardiovascular or neurological disease. Crisis prevention and treatment are focuses of telemedicine in heart failure and [1] proposes a classification of available methods. In [15] tele-care and conventional self-monitored blood glucose programs for titrating the addition of one bolus injection of insulin are compared. In [13] it is described a novel ambulatory system based on inertial sensors for accurate measurement of every stride taken over extended periods for patients affected by Parkinson disease. According to [24] a portable technology provides mobility data that may represent a useful outcome measure for early mobility changes in multiple sclerosis. Accelerometers have been used to assess physical activity that people with stroke undertake in the community and its relationship with walking capacity [16].

Analyzing the gait can be an indirect way to measure people activity and in such a case only global measures are performed (walking speed, balance) [24]. On the contrary, patient's gait can be acquired in much more detail for orthopedic purposes. This is the case of people having walking disorders due do different pathologies or accidents. In particular, the focus of this paper is put on people who had a lower limb loss and use leg prosthesis, either above or below the knee.

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For this kind of applications, both sensors and post-processing of data may be considerably more complex and, thus, may require a structured approach to acquire data correctly and to extract the right output. This is intrinsic to the fact that each step a person performs is a combination of a number of single coordinated movements done in a certain time frame each of which must be captured properly, while in some other medical applications the measure to be taken is much simpler (e.g., body temperature, blood pressure, heart rate).

In order to acquire gait several motion capture (Mocap) techniques can be used. The evolution of Mocap systems as well as of Digital Human Models (DHM) allows a tight integration between the two [17],[7] and, nowadays, in several applications virtual humans are driven by data grabbed from real scenes with people playing a specific role (e.g., in videogames and movie industry). According to the working principles, four main categories can be identified: mechanical, inertial, magnetic and optical. Mechanical ones are the most direct motion capture solutions for gathering human body movements. By the way, it is hard to track the entire body because of the limitations of the sensing devices. The tracking exoskeleton is generally uncomfortable and may limit the range of movements but its overall use is very easy. There are commercial systems available, such as the Gipsy system by Animazoo (www.metamotion.com/gypsy/Animazoo.html). Inertial solutions are based on the use of gyroscopes and accelerometers, usually combined into single inertial measurement units placed on the different body segments. This kind of sensors can only report relative positions of the body and generally suffer of drift problems. Inertial solutions are preferred whenever the person needs to move for long distance or far from the monitoring console, because data can be stored on a memory in the inertial units. Magnetic systems are based on the use of magnetometers or electromagnetic coils to detect the orientation or movement in a magnetic field. This kind of Mocap systems are diffused for tracking body movements of athletes or dancers in reduced volume spaces, while they are not suitable for remote monitoring. Optical systems rely on cameras or other optical sensors to track light sources or reflections or to identify profiles from video frames. Recently, marker-less based systems are becoming more interesting due to their low cost, simplicity and portability. RGB systems without markers rely on the identification of human body silhouette to identify joints and, thus, body segments. Low cost cameras can be simply connected to a generic PC to collect data that can be post processed with free or low-cost software. RGB-D sensors, based on infrared technology are becoming more and more interesting in the research community as well as in industry [18]. The most diffused is Microsoft Kinect, and its use is frequently reported in literature [23],[14],[25]. RGB-D cameras are still less performing than traditional expensive solutions but the huge research effort on both hardware and software development is going to make it the winning solution in the near future.

In this work we applied both RGB-D and inertial sensors. As optical sensors, we used and compared MS Kinect v1, whose working principle is based on the projection and acquisition of an infrared pattern, and MS Kinect v2 based on the Time of Flight principle. The inertial sensors belong to the last generation of devices and allow an accurate measure of movements by means of tridimensional accelerometers and gyroscopes.

3. New proposal

Nowadays, due to a higher complexity, the digital acquisition and analysis of the gait is less diffused compared to other physiological activities. In the majority of medical structures, both hospital and rehabilitation centers, the way a patient walk is assessed empirically by expert personnel eventually supported by low technology means such as video cameras. Tele-monitoring for gait analysis as well is well known but still not widespread, due to the difficulty of measuring and processing of large amount of data.

The novelty proposed by this work consists in easing both hospital and home acquisition of people's movement by using last generation of optical and inertial sensors and to create an almost automated method to gather simple medical indications by processing large amount of geometric data. In this way, the output of a Mocap system can be elaborated to determine the presence of a pathology or a specific deviation from the standard behavior. Gait index can be calculated on quantitative data and some new and more reliable indications can be provided automatically to physicians or orthopedic technicians.

To reach this goal the system must be designed so that it is able to analyze raw data, and to this aim, the knowledge of the expert personnel must be captured, formalized and reused. Thus, the principles of Design Automation must be applied.

3.1. MOCAP technologies adopted

In this work, we used different motion capture sensors in different situations in order to provide a practical evidence of their usability in the orthopedic domain. We used two versions of optical devices available on the market and inertial sensors: respectively, the first version of Microsoft Kinect for Windows, the second version of the same device that was public released in the summer of 2014, and a kit of sensors developed at the University of Bergamo [6].

The first generation of Kinect has an integrated RGB camera with a 640×480 pixels resolution and an infrared camera system that can provide a depth map of the environment, projecting a particular pattern of IR light. In some circumstances, the use of two or more Kinect v1 in the same room simultaneously could create problems in their behavior, because of interpretation errors caused by the overlap of their patterns. The second generation offers a higher resolution camera (1080p) and a different technology, called Time Of Flight (TOF), to create the depth map of the environment. This new technology is more precise and it solves the interpretation errors in the use of multiple sensors for the same scene. The amount of information generated by Kinect v2 is considerable and it needs a USB 3.0 port to communicate with PC (instead of the USB 2.0 required by the first version) [12]. The use of a dual system of Kinect v1 to record a scene, nowadays it is quite easy if we do not consider the problem of the mutual interference, because both sensors could be connected to the same computer. Things change if we talk about Kinect v2. The most important problem, in this case, is that the PC needs to have a USB 3.0 controller and one sensor requires a large part of the bandwidth. This problem has been solved, for the moment, synchronizing information coming from two different devices connected to two different computers and properly merging the results. Both versions of Kinect communicate with the calculator thanks to the Microsoft SDK software, the second version needs the SDK 2.0 that can only be installed on MS Windows 8.

The third type of device we used consists in a kit of five wearable sensors, each of which contains a set of accelerometers. Every sensor has a little plastic case that contains the electronic components and an integrated battery and has a string to secure it to the body. The main sensor is positioned on the body sternum and represents the reference for others, which are fixed in the middle of forearm, arm, shin or thigh. These sensors communicate with PC by a wireless connection and they are lightweight and comfortable because they were ideated for monitoring people with Parkinson's disease and for being use for long lasting sessions. The maximum number of sensors that can be used simultaneously is five; this means that they can be used only on the upper or lower half of the body with two sensors for each limb.

All the experiments were performed in the same laboratory, in a square area of 8 meters per side. In this space, we set up three different configurations to evaluate specific parameters and we made different actors play to collect a proper quantity of data. These configurations are the result of hardware constrains of the sensors, in detail we try to obtain the biggest usable area for the capture. In this phase the set up was complicated by the field of view of the Kinect v1; the improvements made by Microsoft in the second version of the sensor made the configuration easier.

3.2. Scene setup and motion acquisition

Many methods have been proposed to overcome the problems related to the traditional ways Mocap is performed, with the aim of reducing costs, permitting repeatability of the analysis and becoming independent from a laboratory. In particular, inertial sensors have been compared with integrated force plate in shoes [26] or methods with wearable goniometers [20]. Angular rate sensors have been used to monitor during 5 years the gait of patient with total knee replacement [10] or to validate the performance of electronics knee on transfemoral amputee patient during stairs climb [11].

Nowadays, gait analysis is mainly carried out in two methods: in a motion laboratory, with full analysis of the motion of body segments and joints using highly accurate computer based force and optical tracking sensors, or in a doctor's office with the specialist making visual observations. The first method is expensive, requires the maintenance of a dedicated motion laboratory and uses uncomfortable equipment attached to the patient disturbing normal gait, but produces accurate and reliable results for short-distance ambulation. The second method is inexpensive and does not require special equipment, but it is more time consuming. Moreover, results are qualitative, unreliable, and difficult to compare across multiple visits [4]. The proposed method is a low cost solution compared to the expensive optical tracking system and permits to have an automatic procedure to detect defects that affect normal gait.

To accomplish to this goal both scene setup and recording must be done correctly. Scene setup must follow the main guidelines for sensor positioning, environment lightning and actor's cloths. By the way, the positioning of the sensors can be targeted to any specific goal, and for the sake of this work some different scene configuration have been used that were tested in a previous work [19]. The setup has not created unexpected issues, especially in normal gait analysis in which the only occlusions are due to the body of the actor. To avoid occlusions having the actor climbing the stairs the handrails, only for this test, were temporary removed.

The recording of the actors moving in the scene requires complex algorithms to transform the points cloud into the model of a human body for each acquired frame. iPisoft [9] solutions were used to track and

Figure 1. Motion capture devices: a) MS Kinect v1, b) MS Kinect v2, c) wearable inertial sensors.

elaborate data in order to come up with usable results. The acquisition is composed by several phases. The first one consists in reading the background of the scene in order to distinguish and filter it in the following elaborations. Background data can be the same for a number of acquisitions in which nothing changes, but it has to be repeated in case some new objects are introduced, as for the stair in the stair test. The second phase is the recording of the scene with the actor standing still in the T-pose that is required to calibrate the system in accordance with actor's gender and height. Then a rough superimposing of the avatar to the point cloud is manually done and automatically refined by the system. At this stage, the point cloud is moved frame by frame and the avatar automatically updates its position creating, at last, the complete movement of the real actor. The use of more than one sensor requires a calibration stage to gather the relative position of the sensors. This allows to track the scene and to merge the point clouds coming from each sensor. By one side using multiple sensors introduces an error due to the merging of data, but on the other side, it solves the problem of missing information that occurs because segments may be hidden from a single viewpoint. Data gathered can be exported to an electronic sheet or in Matlab format to be further elaborated. Positions, velocities and accelerations both linear and angular have been exported for each of the 27 joints of the reference model of Figure 2.

In the following, two different tests are described that are interesting for the evaluation of the proposed method, for the Motion Capture and for the automatic patient evaluation. In particular, they concern the normal gait on a straight line on a regular flat floor and going up and down some steps on a staircase. The gait test is used to show the feasibility of the automatic detection of gait deviations. The stair test is used only to evaluate acquisition technologies and the evaluation concerning the capability to safely going up and down a stairs will be the subject for further studies.

3.2.1. Gait test

Twelve different actors (10 males and 2 females), as shown in Tab. 1, were asked to walk to test the difficulty in tracking every joint with a single Kinect v1

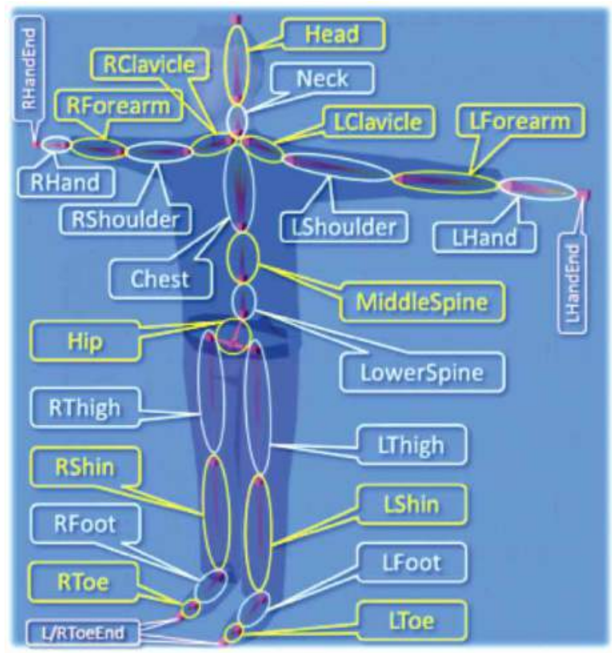

Figure 2. Reference human model with segment names (image courtesy iPisoft).

Table 1. Anthropometric data of people involved in the test.

Actors	Age	Sex	Height [cm]
1	18	F	168
2	18	F	160
3	26	M	185
4	25	M	178
5	26	M	183
6	29	M	178
7	26	M	191
8	39	M	179
9	18	M	178
10	18	M	177
11	18	M	186
12	18	M	171

and v2, instead of the solution with dual sensor acting synchronous. It was not particularly simple to find the "walkable" area that allowed the actors to be taken in every part, especially because of the short range of view of the v1 sensor.

We performed this test also with an actor wearing the inertial sensors on the lower part of the body. It is important to clarify that the inertial sensors represent a good basis for comparison, but they are not perfectly suited for this kind of application since they are designed for a slightly different purpose. Actually, they are affected by some problems and data acquired have not been used for this test. One of the problem is the gimbal lock that is a phenomenon that happens when two rotational axis of an object are pointed in the same direction. It means that the object will not rotate in the desired direction and it lost a degree of freedom.

Fig. 3 shows the resulting output of a gait test in which the right shin rotation respect to the transverse axis (x) is plotted. The measures obtained by different sensors configurations are satisfying and the differences, as expected, never exceed critical levels.

3.2.2. Stairs test

Another test performed is the “stairs test”. We used the Kinects to capture the information of all the human joints, in particular the limb ones. We physically put a five steps stairs in the middle of the field of view and capture four actors climbing up (Fig. 4). In this way, we have position references on the vertical axis, but we could also compare the angles that came from the double Kinect v1 point cloud and the double Kinect v2 one. In the evaluation of the results, it was important to consider and evaluate the influence in the behavior caused by the thickness of the shoe sole.

The stair has 5 identical steps, each one is 13 cm high, so that each step measured on the same foot has a vertical increase of 26 cm. Fig. 4 shows the average data about the vertical position of the right shin of the twelve actors climbing the stair. The stair test provides the chance to compare any acquisition made towards ground true measures, and to precisely measure the error of acquisition.

In this case, the double Kinect v1 configuration overestimates the heights of about 3 cm, mainly due to calibration issues, while the double Kinect v2 error is below 1 cm, which is a good result especially for feet measures.

4. Patients’ evaluation

Since gait analysis nowadays is generally evaluated manually, a number of indexes and methods to determine if a gait is normal or has some defects have been introduced. It is pretty hard to numerically define what can be considered as a normal gait, due to the high variability of each individual. Some of the most relevant metrics for assessing it are Normalcy index [21], Gait Deviation Index (GDI) [22], Gillette Gait Index (GGI) and Gait Profile Score (GPS) [3]. Some of these methods and index have already been applied to evaluate the gait of Lower Limb Prosthesis patients that usually suffers of well-known problems.

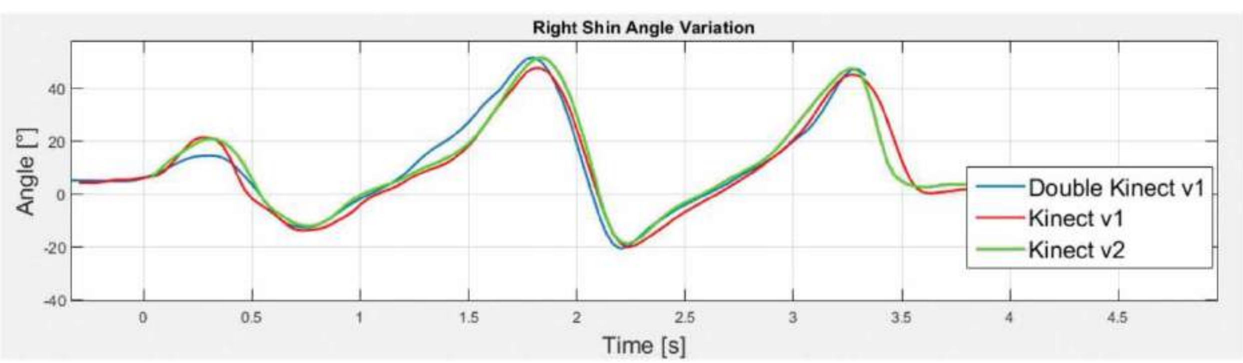

Figure 3. Right Shin angle variation around x-axis.

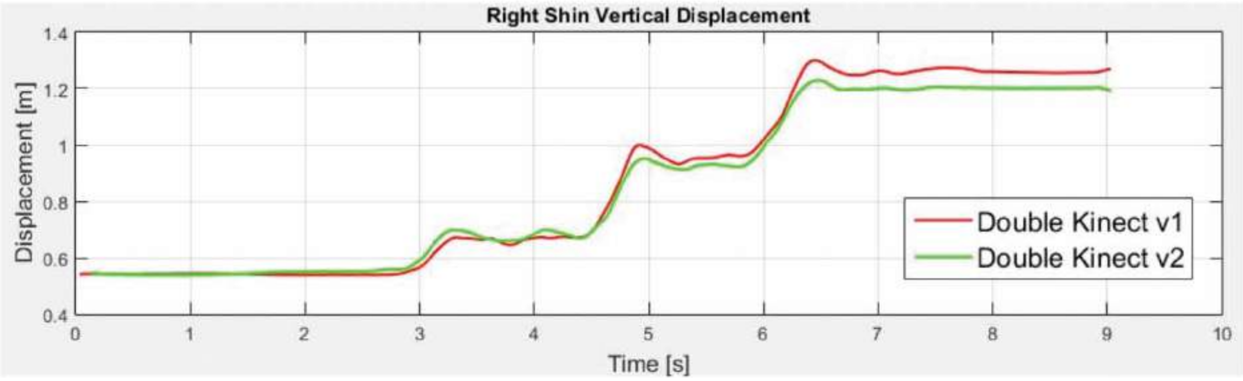

Figure 4. Right Shin joint vertical displacement during stair test.

The approach we defined to assess automatically the presence or absence of gait deviations in an able-bodied or prosthetized person relies on the measuring, extraction and comparing of certain gait parameters in specific moments of the steps with reference parameters stored in a database. This is an empiric approach and its reliability will increase, as the number of acquisition and evaluations gets larger and larger. The parameters to be assessed are much less than those acquired and the most challenging step in this part of the work consisted in defining and extracting the right data subset to be used. The way deviations are defined strictly depends on the Atlas for Prosthetics and to prosthetists knowledge extracted trough a number of meeting and interviews.

The Matlab code developed has different sub processes. The first part is dedicated to the data acquisition from iPisoft. Then, in the second part of the code, the gait is analyzed in order to isolate each step from the others, since the parameters are related to specific frames of each single step acquired. This is performed by analyzing the three joints characterizing the foot: Effector toe, Toe and Foot. Toe joints are used to determine ground level, while Toe Effector is the best joint to detect when the swing phase starts and when it is completed. Analyzing the trends of the three joint it is possible to determine the values delimiting any step and any step phase. At this point, all the meaningful values for each deviation are identified or calculated. Some of these are related to a single frame in which the highest value is reached (e.g. the height of a shoulder), while for others we used global values (step length or duration). At last, the comparison of such values with the reference values is performed to highlight the eventual occurrence of relevant abnormalities.

A form for patient's data input is used and the final results are shown with a simple table in which main data are reported and eventual deviation highlighted so that orthopedic staff can take them into consideration. For instance, the "Lateral Bending" is a walking deviation that occurs whenever the trunk is curved on one side (around the frontal axis). The joint mainly involved for this case is the Lower Spine joint, which is directly connected with the central Hip joint. Using the difference between the average maximum level and the average minimum level of the Lower Spine we can state whether the gait issue is present or not, and, eventually which is the weight of the deviation.

5. Discussion and conclusions

The adoption of optical techniques for Mocap is not new in general purpose applications, but its penetration in orthopedic routine activities is yet to come. Although quantitative gait analysis has become a clinically accepted mean for evaluating and documenting certain pathologies that affect pediatric gait such as cerebral palsy and myelomeningocele, routine clinical quantitative gait analyses are not performed on lower-limb prosthesis users [8]. It is also important to understand that while treatment decision-making is facilitated by clinical gait analysis, these decisions are always made in the context of the clinician's experience in gait analysis and in the management of the particular disorder presented by the patient. Thus, the maximum extent of this research work is to provide technicians with a decision-making aid based on formalized experience (e.g. the Atlas of Prosthetics Limbs [5]) and on best practices. The introduction on a broad scale of quantitative data analysis of gait will promote a more scientific approach to the use of such data for physicians' decision-making.

Among the technological barriers, some of which overcome by recent technological advancements, the psychological inertia to a change of paradigm and the low level of skills in information science of the medical staff create a gap among technology potential and real exploitation. The aim of this study consists in showing how low cost accessible Mocap technologies could improve dramatically the way gait analysis are performed. Setting up a Mocap laboratory using videogame-derived sensors and state of the art PC and performing a codification of orthopedic knowledge on walking dynamics it has been possible to change the assessment of patients gait making it digital and automatic. Our main concern were the accuracy of the Kinect sensors and the tests done with twelve people gave good results, both on the comparison of two generation of sensors (Kinect v1 and Kinect v2) and respect to ground true measures. We adopted a kit of inertial sensors as well, even if for this specific use the optical solutions are preferred. The inertial system, actually, require at least 9 sensor to map the whole body and the relative positioning on body segments is crucial to gather good results. The starting hypothesis was to consider the use of optical system in a dedicated laboratory where some simple tasks can be done by a technician (e.g. calibration) and to propose inertial sensors for an independent home use but this second condition is not yet reliable for this specific purpose. Actually, even if wearable sensors are perfectly suited for home use and they are already adopted for several medical monitoring activities, the assessment of the gait is not yet one of these. The main purpose is the elevated number of sensors and the sensitivity of the measure to the position of the sensors on the body.

The use of depth optical sensors in a dedicated facility, on the contrary, allows quick and non-invasive acquisition of a patient's gait. What we showed with this study is that by introducing proper data elaboration and embedding some orthopedic knowledge in an ad-hoc software module automatic detection of abnormalities can be performed. We applied this approach to the case of people having a lower limb prosthesis, their deviation from a standard walk being more noticeable, but the same approach can be extended to able-bodied people. The main drawback is that the procedure requires a robust database to compare results acquired, detailed for men, women and children, and eventually taking into account of pathologies and special conditions. By the way, the adoption of this approach itself to a broad scale could be the way to populate such a database. A secondary limitation may be due to the accuracy of the measures obtained with optical systems, but this has demonstrated to be generally sufficient now, and it is going to improve in the future as it is linked to video-gaming industry. Further developments are required to introduce this approach in everyday medical practice. Actually, the work we have done relies on iPisoft and on Matlab for acquisition and the first elaboration of data and, then, for gathering the final output. A single environment, at least for the user interface, would be much better to reach the minimum level of usability by non ICT experts. Once reached a good level of robustness the approach could be used for the automatic screening of a large number of people in public places, for instance, in schools to prevent gait deviations and the effects an incorrect gait could provoke.

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