On Different Approaches to Human Body Movement Analysis

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Abstract. Biomechanics of human gait belongs to the biometric recognition systems for identification/recognition of people for various security applications. The method itself is not new, but its utilization in real world is still not in its maximum, especially due to a time-consuming processing and a demand for reliable algorithms. We focus on unique manifestation of gait patterns and their equability under different conditions of walk in our basic research. As the movement of each selected segment of human body is generating curves in space, the basic statistical methods cannot be utilized as they do not have predicative value due to incorrectness of used principles on curves analysis. Thus, we incorporated the functional analysis to obtain proper results.

Keywords: VICON, gait, functional analysis, biometrics, pattern recognition, ANOVA, statistics.

1 Introduction

Analysing the human gait is very time demanding area not only from the side of physicians, but from the overall scientific point of view. As the human gait is very variable between each point on the one human body, but said to be consistent and invariant between persons its correct analysis is necessary. When dealing with analysis of human gait for security purposes, the result of such analyses must be as precise as possible as utilization of incorrect biometrics (in our case gait patterns) may cause problems during and after implementation into praxis.

Until now, the most attention was dedicated to development of algorithms for automated gait recognition software. The studies of gait patterns changes were done mainly for the purposes of rehabilitation, proper treatment of injuries and health problems and monitoring the health states of patients after strokes, paralyses, surgeries, etc. Unfortunately, only few studies or theses dealt with changes of gait patterns during various conditions. Those studies include: changes in gait during menstrual cycle [1], between dressed and light clad participants [2], genders, age, race, acoustics of gait on different surfaces [3,4,5], changes during various speeds [6], influence of rehabilitation tools [7], diseases [8], rehabilitation after diseases [9], changes in elders [10], effect of shoes [11], behaviours during sports [12], effect of poor sight [13], therapy effects [14], and analyses like electromyography [15], comparison of tools [16], new equipment [17], variability for biometric purposes [18], and many other (e. g. testing robots, adapting algorithms to obtain higher functionality of software solutions).

These experiments more or less proved that the gait patterns are personally unique and therefore can be used as biometrics; although it is not yet clearhow useful gait can be for biometrics in larger scale. These studies can be divided into two main categories – sensor-based (especially medical researches) and video-based (most often silhouette or model based image testing). When talking about classical statistical analyses, the most frequently analyses employed are well-known parametric tests,TuckeyHSD test, correlation factor-coefficients, Euclidean distances, multivariate data analysis, Fourier transformations and ANOVA. These statistical tests are used in majority of the researches providing acceptable results. A different approach contains statistical evaluation by functional analysis as functional data are often multivariate in a different sense. The basic philosophy of functional data analysis is to consider each function a single entity. Body movement sets of functions (curves in datasets) are periodic and functional analysis can serve us with smooth functions, their interactions, highlighted various characteristics, exploration of overall variability in functional data, comparison of data sets with respect to certain types of variations and explanation of variations in an outcome or variable [19]. The functional analysis can therefore answer better the requirements for proper gait data analysis.

This paper introduces compendium of different approaches to gait analysis based on curves (functions) gained from a 3D motion capture systems with markers on chosen body parts and participants passing the "catwalk" (corridor). The Methods section also describes some requirements for measuring on such system to avoid unnecessary problems with processing the data statistically.

2 Methods

2.1 Participants and Data Acquisition

The minimal amount of participants for security and other purpose analyses are 10, ideal number is 25+. However, this number is not very sufficient from the statistical side of view. The problem with higher amount of people in dataset is a time demandingness of processing acquired data. If we talk about analyses for security purposes, participants should have no serious pathology, injury or any posttraumatic history in their musculoskeletal system prior to the measurement. On the other hand, when measuring clinical trials for condition or health analyses, it is good to have a template gait (or body segment) functions that are from a healthy people to have contrast to the one with issues.

Apart from amount of participants in our trials, it is also necessary to calculate with number of double-steps in one trial. The minimal number is, according to [21], 10 cycles of single double-steps. To obtain this amount, the minimum trials to go is 10, but our recommendation is to do at least 20 trials, as some of the markers' functions

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can be missing and/or with errors, and it is not possible to expect which ones and when will do so during the single experiment. We must also bear in mind that the possibility of inapplicability of some participants occurs, even though this error rate is very low.

Another parameter that must be taken into account is the shape of monitored area/corridor and the cameras disposition in the space. Cameras should be disposed equallyto the movement recorded to be able to depict all of markers continually as they move in the space. Fig. 1 shows some of the ideal camera set-up.

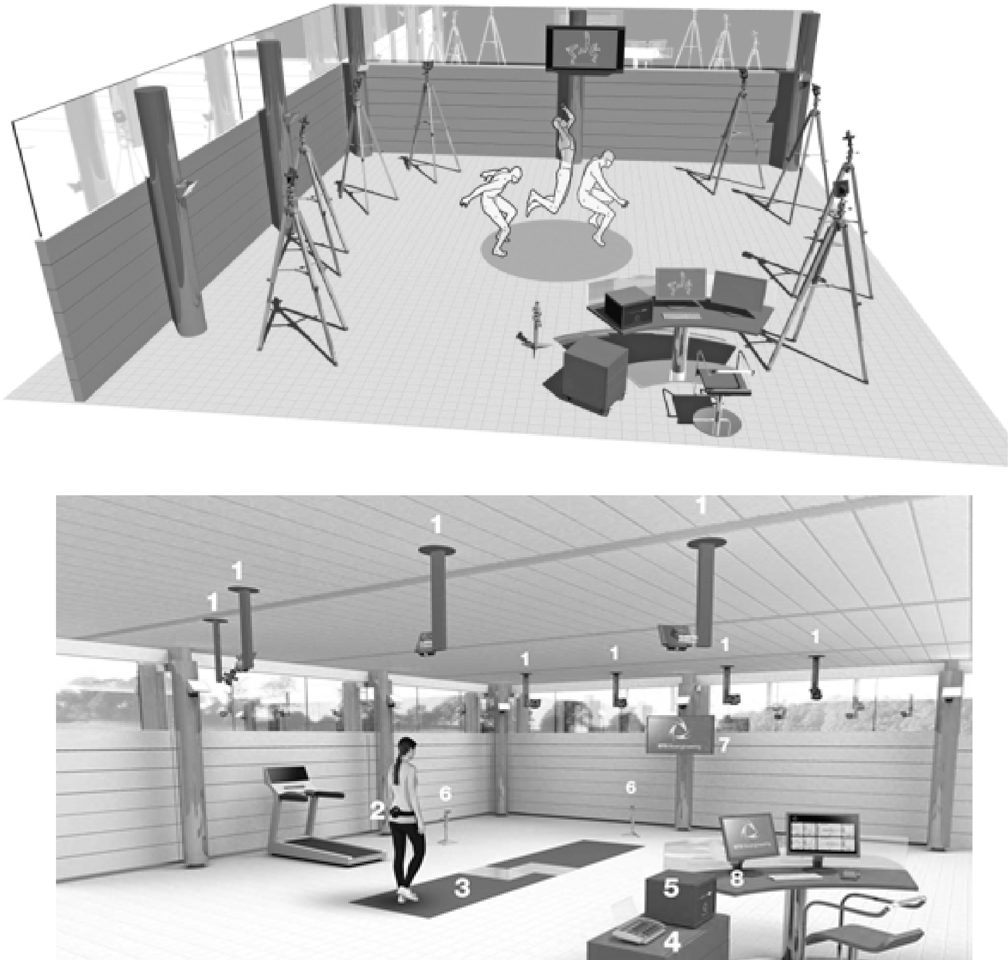

Fig. 1. Examples of ideal indoor camera set-up [31]

The most utilized systems for 3D motion capture are BTS SMART, VICON, and QUALISYS. The movement is captured by 2 - 16 cameras with infrared filters detecting passive markers placed on human body in the area. For the self-analysis in security, a double-step (one stride cycle length) is usually chosen, although in some cases two or three cycles are captured. The height of cameras is between 1.2 – 2.5 m depending on the focused markers, and the frequency should be minimally120 fps.

The commonly used models includes more than 35 markers (ø 3- 25 mm depending on our research intentions) placed on anatomically significant places (based on walk analysis protocols: Davis, Helen Hayes, Newington, Lamb, Cast, Foot Model), position of markers used for this part of research can be seen in Fig. 2. Those parts, respectively their widths/lengths together with the basic anthropometric data are defined before the beginning of experiments for accurate calculations.

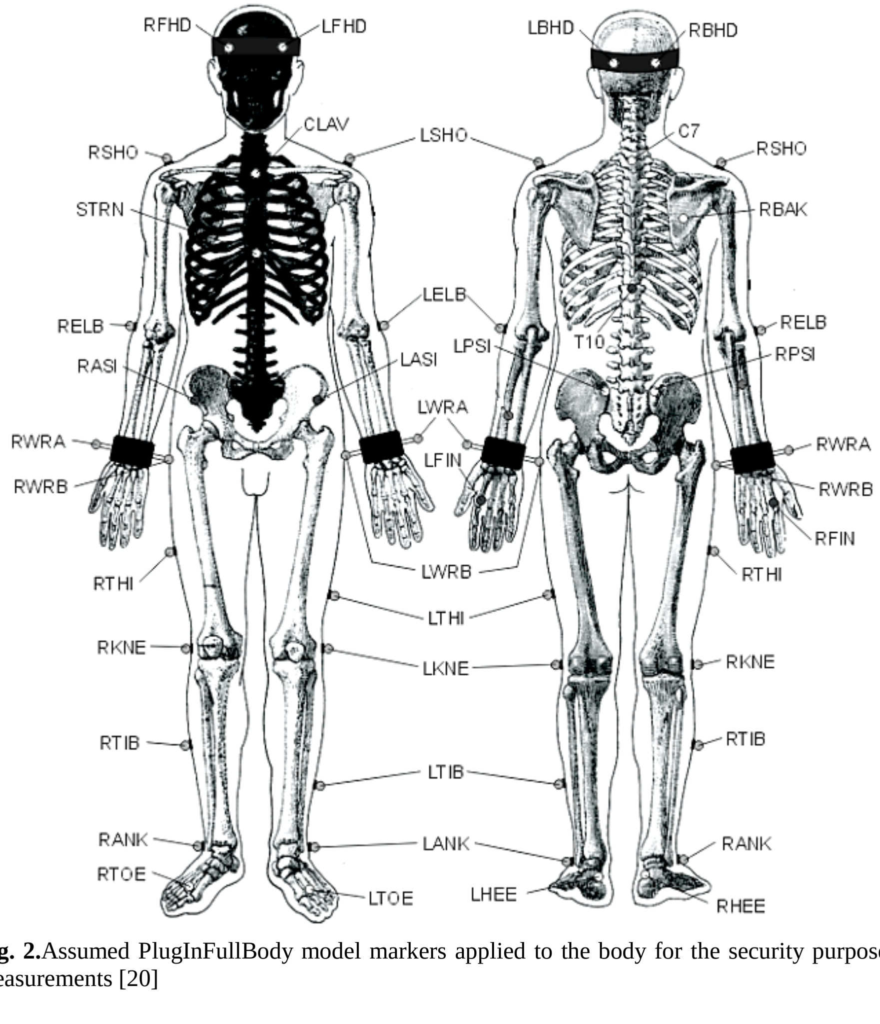

Fig. 2. Assumed PlugInFullBody model markers applied to the body for the security purposes measurements [20]

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2.2 Data Analysis

Recordings of pass-troughs are rendered, smoothed, filtered, calculated and if required normalized by the software usually enclosed to the system. The initial contact and swing phase of stride cycle is detected where it is possible according to the force plates, or they can be found in the exported spreadsheets through heel markers surface contacts in other cases. All measured data can be converted into *.CSV and similarformats to be used for further calculations/testing in the MS Excel, statistical software (STATISTICA, R, SAS/STAT, etc.),Matlab or others.

2.3 Functional Analysis [19]

This chapter will briefly introduce some basic approaches to functional analysis, which is highly suitable for gait pattern analysis.

The record of the function x_i might consist of $n_i$pairs (t_{ij}, y_{ij}), $j = 1,\ldots,n_i$, and takes place separately or independently for each record i.

The sampling rate or resolution of the raw data shows us what is possible in the way of the functional data analysis. This can be displayed by the curvature of a function, which is usually measured by the size of second derivative. The higher the curvature, the better estimation of the function. The sufficient sampling rate for gait data is c. 20 values per cycle. Unfortunately, too high rate may cause serious problems.

$$|D^2x(t)| \ or \ [D^2x(t)]^2 \qquad (1)$$

The first step in functional analysis is the smoothing and interpolation of the data. If the data are assumed to be errorless, the process is called interpolation, but in our case we suppose some observational errors that need removing, so the conversion from discrete data to functions may involve smoothing to function x_i witch values $x_i(t)$ computable for any desired argument value t. This can be done by roughness penalty smoothing method or by using smoothing splines.

One of the next steps is displaying the result of analysis, where different displays of data bring different features of interest and information. One of the possibilities is also to plot pairs of derivatives to get the relationship between derivatives: the exponential function

$$f(t) = C_1 + C_2e^{\alpha t} \qquad (2)$$

satisfies the differential equation

$$Df = -\alpha(f - C_1) \qquad (3)$$

and the sinusoid

$$f(t) = C_1 + C_2\sin[\omega(t - \tau)] \qquad (4)$$

with phase constant τ satisfies

$$D^2f = -\omega^2(f - C_1) \qquad (5)$$

Plotting the 1st and 2ndderivative against the function value explores the possibility of demonstrating a linear relationship corresponding to one of these differential equations. Plotting the higher derivative against lower is more informative due to departures from linearity and exposure of effects that are cannot be easily seen in original function.

The classical summary statistics for univariate data applies equally for functional data. The mean function with values

$$\bar{x}(t) = N^{-1} \sum_{i=1}^{N} x_i\,(t) \quad (6)$$

is the average of the functions point-wise across replications. The variance function *var* is then

$$var_X(t) = (N-1)^{-1} \sum_{i=1}^{N} [x_i(t) - \bar{x}(t)]^2 \quad (7)$$

and the standard deviation function is

$$\sqrt{var_x(t)} \quad (8)$$

The covariance function summarizes the dependence of records across different argument values, and is computed for all t_1 and t_2

$$cov_x(t_1, t_2) = (N-1)^{-1} \sum_{i=1}^{N} \{x_i(t_1) - \bar{x}(t_1)\}\{x_i(t_2) - \bar{x}(t_2)\} \quad (9)$$

The associated correlation function is

$$corr_x(t_1 - t_2) = \frac{cov_x(t_1,t_2)}{\sqrt{var_x(t_1) var_x(t_2)}} \quad (10)$$

If we had pairs of observed function (x_i, y_i) their reciprocal dependency can be quantified by the cross-covariance function

$$cov_{X,Y}(t_1, t_2) = (N-1)^{-1} \sum_{i=1}^{N} \{x_i(t_1) - \bar{x}(t_1)\}\,\{y_i(t_2) - \bar{y}(t_2)\} \quad (11)$$

or the cross-correlation function

$$corr_{X,Y}(t_1, t_2) = \frac{cov_{X,Y}(t_1,t_2)}{\sqrt{var_X(t_1) var_Y(t_2)}} \quad (12)$$

The Fourier basis system for periodic data is provided by the Fourier series

$$\hat{x}(t) = c_0 + c_1 sin\omega t + c_2 cos\omega t + c_3 sin\omega t + c_4 cos\omega t + \cdots \quad (13)$$

defined by the basis $\emptyset_1(t) = 1$, $\emptyset_{2r-1}(t) = sinr\omega t$ and $\emptyset_{2r}(t) = cosr\omega t$, where ω determines $2\pi/\omega$.

Functional linear models investigate the way in which variability in observed data can be accounted for by other known observed variables. They can be all placed within the framework of the general linear model

$$y = \boldsymbol{Z}\beta + \epsilon \quad (14)$$

where y is typically a vector of observations, β is a parameter vector, **Z** is a matrix defining a linear transformation from parameter to observation space, and ε is an error vector with mean zero.

The principal component analysis for functional data started with combining a weight vector β with a data vector x to calculate the inner product

$$\beta' x = \sum_j \beta_j x_j \quad (15)$$

When β and x are functions *β(s)* and *x(s)*, summations over *j* are replaced by integrations over *s* to define the inner product

$$\int \beta x = \int \beta(s) x(s) ds \quad (16)$$

Using (16) the principal component scores corresponding to weight β are now

$$f_i = \int \beta x_i = \int \beta(s) x_i(s) ds \quad (17)$$

by choosing the $\xi_1(s)$, following equation is maximized

$$N^{-1} \sum_i f_{i1}^2 = N^{-1} \sum_i (\int \xi_1 x_i)^2 \quad (18)$$

subject to the continuous analogue of the unit sum of squares constraint

$$\int \xi_1(s)^2\, ds = 1. \quad (19)$$

3 Results and Discussion

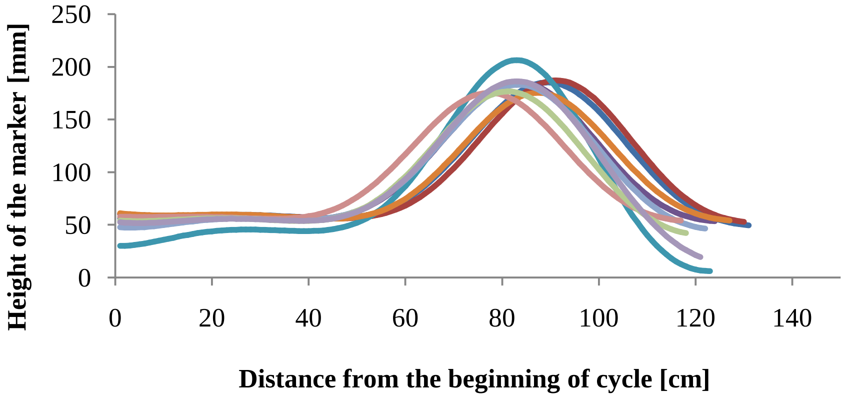

Fig. 3. Correct trajectories of left ankleof one person during normal gait cycle[author]

In our preliminary research [32], we discuss the differences and resemblance of 11 people (5 women, 6 men; all healthy) during eight various conditions. We used classical statistical methods that are used across the literature. Results were according to our expectations, though it was shown that the gait differs from the average in extreme conditions (too slow and fast walking, first three passages after workout) and the markers can be interchanged (even between men and women) or shifted in a way that may be in some cases positions of marker above or below.

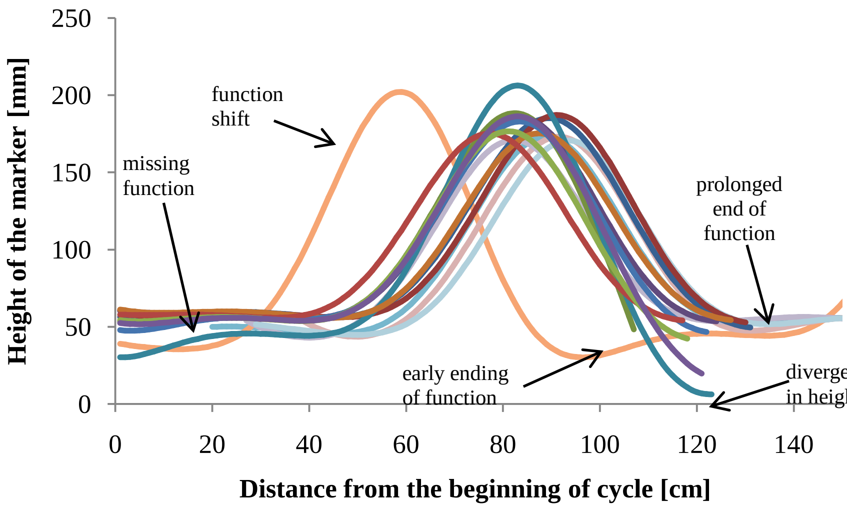

Fig. 4. Trajectories of left ankle with errors and missing parts of functions of one person during normal gait cycle [author]

However, some issues during data processing occur and therefore we were unable to use the rest of our data (another 10 people), as they contain serious errors (Fig. 4-5) or missing marker functions, or missing bigger parts of marker functions in cycles (e.g. the marker C7 is in 98 % of cases ill-structured; in some participants, there are only two functions of toe marker in men 1 and normal gait as the marker heights are shifted to the level of hips). This happened even though we were very precise during marker placing and 3D data acquisition. These errors occur not only in dataset with distances, but also in datasets with angular and time data. Most of these errors are impossible to be fixed manually. What is more, the most unexpected issue is that the errors occur in full body parts movements where all other markers are correct, not only in partial movements where we occasionally expected them. All of these functions were exempted from the testing dataset available for further analysing. Nevertheless, some errors in functions also arise due to extreme walking conditions and are therefore in such cases retained in datasets.

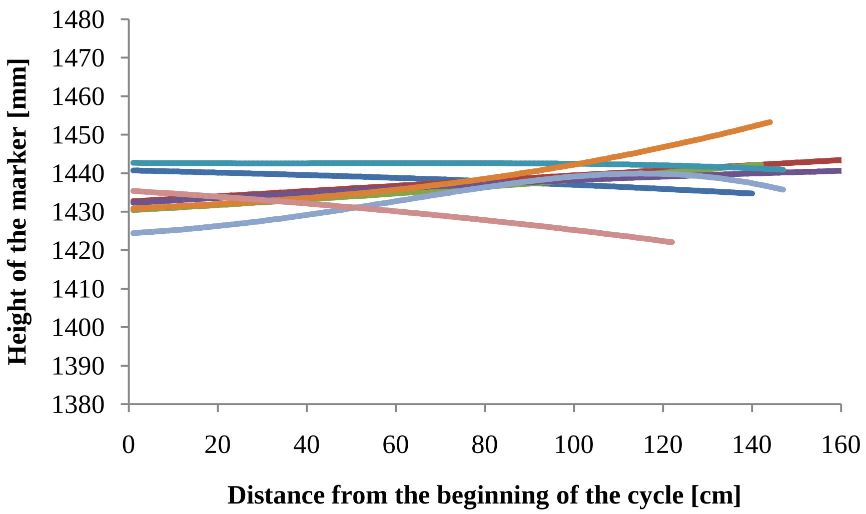

Fig. 5. Trajectories of C7with ill-structured functionsof one person during normal gaitcycle [author]

Some of these problems probably arose from a software failure of the VICON mocap software. However, most of the errors in functions are hardly explicable. Trials where a marker was unstuck (3 cases) or the person was not walking as planned (1 case) were removed. In two cases, data are entirely unavailable as the participants did not hit the force plates and the software solution was unable to build up the model. Therefore, we would like to make proposal for consequent measurement:

- each person undergo at least 30 trials (including hitting the force plates) to each 7 correct trials,
- the corridor (space) should be approx. 8 meters long,
- markers for people that sweat a lot must be fixed by highly sticky tapes (probably assembling ones),

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- an extra marker stacked in the middle of a forehead and both earlobes (for security purposes recognition),
- processing data in mocap software immediately after the daily measurement to get the necessary feedback and if possible re-measure needed number of trials.

4 Conclusion

The possible utilization of the gait analysis and recognition is great. The gait analysis has its place in many parts of our lives beginning with the biomechanics and ending with the field of virtual reality. The time saved by tests made in the 3D environment is invaluable asthe 3D gait analysis can save time and money expended on redundant surgeries, prevent from injuries in many sports, including people as well as animals.

The contribution of gait as a biometrics may be after obtaining data set of the gait patterns big enough invaluable.However, after big data collection of gait patterns, it could be said whether the successful gait recognition for security purposes in great extent is possible or not. So far the variability of the gait appears to be big enough, but further testing with a greater amount of people under different conditions is necessary.

The future may contain the biometric recognition based on the gait analysis, where ill, injured or endangered persons will be detected automatically by a remote surveillance; and violators, ambushers, terrorists and other suspects will be detected before they will have an opportunity to harm or damage protected interests. Such future could have, on the other hand, some disadvantages – mistaken identity, falsely accused people, lack of freedom in some way, protests against such surveillance, and many more. It will be necessary to consider all the pros and cons[25], public opinions and overall morale of the population in the country. We must always bear in mind that no system is perfect and everything is exploitable, even though it was originally intended for a good thing.

Our further research focuses on gait patterns analyses by means of functional analysistogether with mixed models to obtain accurate results that will be used not only as another resource for assessment of applicability/inapplicability of gait as a biometrics, but will be also used in further security projects at our university dealing with marker-free video recognition. The data will not be chosen by whole body part complex movement, but will be selected separately to derive as much correct functions as possible for accurate functional analysis. Results of these analyses will be published to make available knowledge arising from direct application of these analyses to broad public dealing with gait patterns recognition and to show their awaited benefits.

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