A Public Dataset of Overground and Treadmill Walking in Healthy Individuals Captured by Wearable IMU and sEMG Sensors

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Abstract: The paper presents our public Gait Analysis Data Base (http://gaitanalysis.th-brandenburg.de), which contains 3D walking kinematics and muscle activity data from healthy adults walking at normal, slow or fast pace on the flat ground or at an incremental speeds on treadmill. The acceleration, angular velocity and magnetic rate vectors are measured using XSens MTw sensors attached to both feet, shanks, thighs and the pelvis. EMG recordings are acquired using PLUX sEMG sensors applied at various leg muscles. The paper gives not only a detailed description of the data base, its webpage and the used terms (scenario, proband, experiment and trial), but also an overview about the experimental setup, the acquisition of data and the procedure of the experiments, the data processing and evaluation. Results of exemplary applications are described in the second part of the paper. Here the focus is set on the performance of walking: the individual ability to control, to repeat and to reproduce the pace or the dependence of gait parameters on the pre-set velocity.

1 INTRODUCTION

Since 2000 the platform PhysioNet[1] offers free web access to large collections of recorded physiologic signals (PhysioBank) and related open-source software (PhysioToolkit). PhysioNet is an online forum for the dissemination and exchange of recorded biomedical signals and open-source software for analyzing them. It provides facilities for the cooperative analysis of data and the evaluation of proposed new algorithms (Goldberger et al., 2000).

Gait databases[2] contain stride interval (gait cycle duration) time series in text form.

Data sharing and increased acceptance of replication studies have been advocated to overcome experimental limitations and to validate the inferences made by previous gait studies (Ferber et al., 2016; Knudson, 2017). Only a handful of walking biomechanics datasets have been made publicly available (Hnat, Moore & Van den Bogert, 2015; Kirtley, 2014; Willson & Kernozek, 2014). There is an objective need to share data and to have normative databases to improve and to evaluate the interpretation of gait analysis outcomes. In the 1990s the first gait datasets were made available (Winter, 1993; Winter 2009; Perry, 1992), including patterns for joint angles, joint moments and reaction forces, later patterns of muscle activities were added (Bovi, 2011).

The MMClab[3] of the University of ABC, Brazil, provides a public dataset of 3D walking kinematics and kinetics data on healthy young and older adults at a range of gait speeds in both the treadmill and overground environments. The datasets include both raw and processed kinematic and kinetic data (Fukuchi et al. 2018).

Our GaitAnalysisDataBase[4] contains 3D walking kinematics and muscle activity data from healthy adults walking on the flat ground or at a treadmill. The acceleration, angular velocity and magnetic rate vectors are measured using inertial measurement units (IMU Xsens MTw[5]) applied to both feet, shanks, thighs and the pelvis. EMG recordings are acquired using acceleration and surface EMG sensors (PLUX XYZ and PLUX[6] sEMG) applied at various leg muscles. The data sets include unfiltered, gravity compensated kinematic data of Xsens sensors and

[1] http://www.physionet.org
[2] https://physionet.org/physiobank /database/#gait
[3] http://demotu.org/datasets/walk/
[4] http://gaitanalysis. th-brandenburg.de
[5] xsens.com
[6] plux.info

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unprocessed raw data of PLUX acceleration and sEMG sensors.

The GaitAnalysisDataBase collects data sets acquired under the supervision of the authors during the last years at the Brandenburg University of Applied Sciences (THB), at FH Vorarlberg (Austria), at the University of Oulu (Finland) and at MMUST (Kenya), indoor and outdoor, on paved and unpaved trails, at various climatic conditions, investigating various aspects of human movement.

Students and professors, technicians and researchers have been involved in the process of preparing and executing measurements as well as in storing and evaluating the acquired data. All these volunteers – healthy adults between 18 and 65 from several nationalities – provided informed consent about the experiments, data storage and the future use of data.

Following the initial idea of the PhysioNet platform, the GaitAnalysisDataBase are meant to facilitate "the cooperative analysis of data and the evaluation of proposed new algorithms", to support the development of robust algorithms and to be used for teaching and other educational purposes. The data were collected by lecturers and students guided by prescribed procedures and checklists. Recordings containing measurement errors or procedural faults, caused by equipment, subjects or instructors, have not been excluded. They should be detected by automatically proceeding and robustness algorithms. The data sets serve as useful examples for testing newly implemented algorithms.

The paper is divided into two main parts: the description of the public dataset and exemplary applications to demonstrate possible investigations using the provided data. This paper is not intended to explain all aspects of the developed methods/algorithms, including all related to them problems, and to discuss the results of the exemplary applications. More details are presented in e.g. Loose (2015) and Loose et al. (2016).

2 SYSTEM AND EXPERIMENTS

We have focused on human walking, tried to understand the underlying process and to find the best positions of sensors. Robust and reliable algorithms which apply to a wide range of walking scenarios (~2-8 km/h) were developed. The algorithms were evaluated on data sets acquired from IMUs attached to the foot, shank, thigh, pelvis or from sEMG, applied to various muscles, supplemented by an accelerometer placed at the heel. Two main scenarios - repetitive walking on the flat ground and walking on a treadmill - were addressed with a large number of healthy subjects.

2.1 Experimental Setup

The Xsens sensors are clipped on body straps attached similarly on the left and right lower limbs and one in the middle of the back. Typically one pair is sitting on the metatarsus, two directly above the ankle and the knee. The distances of the sensors from the floor, as well as the length of the limbs are stored in the subject's individual experiment record.

Figure 1: Experimental setup – Xsens and PLUX sensors are applied.

When PLUX sensors are included in the experimental setup, sEMG pads are (mostly) positioned accordingly the recommendations of SENIAM [7] symmetrically on muscles involved in locomotion activities,: m. gluteus maximus, m. rectus femoris, m. biceps femoris, m. vastus lateralis femoris, m. vastus medialis femoris, m. tibialis anterior, m. tibialis posterior, m. gastrocnemius lateralis, m. gastrocnemius medialis, m. soleus. Accelerometers are applied to the heel to supplement sEMG records.

[7] http://www.seniam.org/

2.2 Sensors and Software

During the gait analysis courses three generations of the 9DOF Xsens MTw sensors have been used to acquire accelerations, angular velocities and magnetic rates as well as the sensor orientation at a sampling rate between 60 and 100 Hz. Two generations of the PLUX equipment have been applied to record muscle activities (sEMG) and the related acceleration at a sampling rate of 1 kHz.

2.2.1 Xsens MTw Sensors

The 9DOF Xsens MTw sensor (Roetenberg, 2009) incorporates three microelectromechanical sensors: triple-axis gyroscope, accelerometer and, magnetometer.

Onboard the data of the primary sensors are sampled with 1800 Hz, strapped down by integration (SDI) incorporating the estimate of orientation to the transfer rate 60 Hz for seven sensors or 100 Hz for two sensors (first generation).

The MTw are connected via Bluetooth to one Awinda station and the data acquisition software “MT Manager, versions 3.81, 4.21 and 4.9”.

All involved sensors are synchronized with high accuracy (< 0.01 ms). The software provides linear acceleration a, angular velocity ω, magnetic field m and quaternion q (estimated on-board with < 1° of static and 2° RMS of dynamic accuracy).

Before the measurement the sensors need a calm or slow motion for calibration, to determine the initial orientation of the sensor with respect to the world coordinate system.

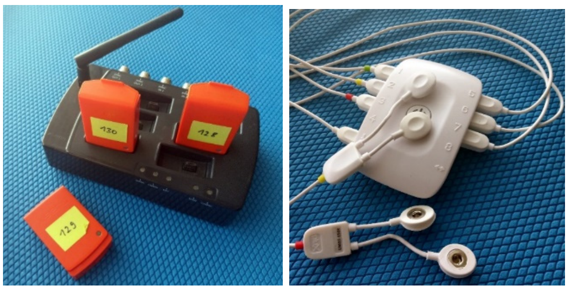

Figure 2: IMU Xsens Mtw sensors and AVIRA unit (left) and PLUX Channel hub and connected sensors (right).

2.2.2 PLUX Sensors

The PLUX biosignal kit[8] includes a wireless 8 channel hub, various sensors and the data acquisition software "OpenSignals". The non-filtered sensor data were acquired at a sampling rate of 1 kHz.

In most of the experiments, 5 sEMG and a triaxial accelerometer sensors were connected to a hub (one for each leg), sometimes two similar hubs were used simultaneously.

2.3 Scenarios

All data sets have been acquired in two main scenarios:

- “The Catwalk”: walking a distance of mostly 20 m (in a range of 10 m to 80 m) on flat ground at usual/normal, reduced/slowed and increased/fast speed,
- “The Treadmill”: walking on a treadmill at incremental speed settings from 3.5 to 6.5 km/h or 2 to 8 km/h).

The specifications of the experimental setup for each dataset is given on the GaitAnalysisDataBase website and is included in META data of any record.

A test scenario was involved in the examination of distance accuracy: Straight forward, steady walking outdoor on a long enough distance (~175 m), on flat and paved ground. The distance was measured alternatively with GPS and tape line. The trial was repeated twice.

2.4 Cohorts

Study participants included 108 healthy volunteers between 17 - (average: 26, median: 23) - 63 years old, 147 – (174) – 194 cm height, 54 – (76) – 120 kg weight and a body mass index of 19 – (24) – 37. There were 45 females and 63 males. Figure 3 shows the distribution of age, height, and weight of all volunteers. The 0 kg bin is caused in the lack of data in one scenario.

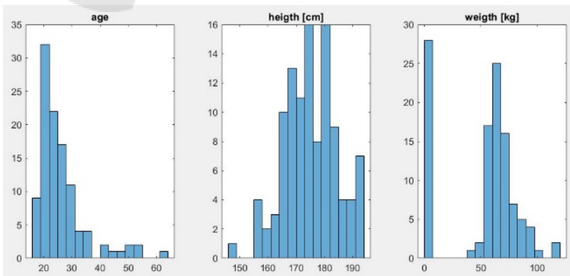

Figure 3: Age, height and weight distribution.

Only in 2017 (March – October) a subject was monitored during the recovery process after the surgery caused by a fibula fracture (“Cat walking” and “Treadmill).

[8] https://plux.info/12-biosignalsplux

2.5 Procedure

All gait trials were performed in everyday conditions, and the participants were comfortably dressed. Before data collection, each participant received a brief explanation of the study and signed the consent form. Body height and body mass were measured. The year of birth was asked.

Each recording was started and terminated with a three second calm phase independent of whether the subject was walking on flat ground or on the treadmill. Each trial is recorded and stored separately. The subject is asked to stop at the end of a trial and not to turn or to move before the recording is terminated.

2.6 Evaluation

All algorithms used in all steps of data evaluation were developed, implemented and tested in MATLAB® [9] by ourselves. An open script is organized to process experimental data automatically step by step. After each step, the intermediate results are saved.

The developed algorithms are designed on a robust stride detection and a stride-by-stride determination of derived characteristics allowing recalibrations at the beginning of each stride.

The term "stride" or "gait cycle" is defined as the period between two successional gait events. Perry (Perry, 1992) and others defined the initial contact, i.e. the moment of the heel strike, as the beginning of the gait cycle. To choose the period from mid-stance to mid-stance for calculation is more constructive, because at this moment obviously the foot is not moving, it stands on the floor and the leg is vertical elongated.

2.6.1 Xsens Sensor Data Processing

9DOF Xsens MTw sensors provide accelerations, angular velocities, magnetic rates and orientation data. The sampled data of all involved in the trial sensors are received by the Xsens MT manger via Bluetooth and stored in one proprietary file. This data file is exported in text csv-files, one for each sensor.

The data of each Xsens sensors are evaluated separately. The following steps are included:

- Pre-processing: reading and reorganizing the acquired data, given in the sensor related coordinate system (SCS), transformation of sensor data into world coordinate system (WCS), elimination of gravity, calculation of orientation relative to the initial one, calculation of angles between z-axes of a sensor and the vertical or the horizontal plane, calculation of joint angles.
- Processing: estimation of direction of motion, calculation of candidates for gait events, plausibility check, determination of gait cycles, transformation of data into motion coordinate system (MCS), integration of acceleration, calculation of velocity and position data stride by stride.
- Post-processing: calculation of stride related and average features, determination of average motion.
- Evaluation: building figures, extracting and processing tables.

The database contains the pre-processed datasets of each sensor. Additional the following computed parameters are available at the website: duration in [s], distance in [m], cadence in [steps/min] and number of strides. Other features are determined during post-processing and evaluation.

Remark: All sensors are treated in the same way independent on their position. Because of this the calculated velocities do not include the steady part of motion, which is zero for the foot sensors. The steady motion increases together with the height of the sensor position (see Loose, 2015).

2.6.2 PLUX Sensor Data Evaluation

sEMG sensors were mostly used in combination with XYZ accelerometers placed at the heel, sometimes without them. The following two different approaches to detect gait cycles were implemented. If an XYZ accelerometer is used the outstanding local minima related to the heel strike are determined and the signals are partitioned beginning and terminating at heel strikes. Otherwise the main frequency of all available signals is calculated. The correspondent period of time (average stride duration) is taken to partition them.

The following steps are included:

- Pre-processing: reading, reorganizing and conditioning the acquired data, calculation of sEMG envelopes based on rms-methods.
- Processing: determination of gait cycles, partitioning sensor signals and envelopes.
- Post-processing: calculation of mean and median frequencies, power spectrums and energy characteristics, determination of average curves.

[9] www.mathworks.com

- Evaluation: building figures, extracting and processing tables.

3 ORGANIZATION OF THE DATA BASE

The data sets collected in the database were acquired by lecturers and students, in undergraduate and graduate courses dealing with various aspects of gait analysis, experimental and evaluation methods. In each course the scenario, the experimental setup and the procedure of the trials were explained and discussed with all participants. The execution of the experiments following pre-defined checklists has been supervised by the lecturer (authors). Any measurement errors or procedural faults, caused by equipment, probands or instructors, were noted and were excluded only in the case that nothing substantial was recorded. They serve as useful examples for testing the robustness of algorithm implementations.

Before getting access to the database, the user needs to register in the system entering his username, password and email address. Later he can sign in by username and password. The personal data of the registration are used only for statistics about access to the database.

3.1 Terms

The most important terms in the database are scenarios, probands, experiments, the chosen experiment and the individual recordings.

A **Scenario** describes the conditions of all experiments proceeded during a course: overground or treadmill, speed levels, used sensors, number of trials.

A **Proband** relates to a real person participating in one or more experiments. Any proband has an individual ID "Pxxx".

An **experiment** relates to one scenario and one proband. It groups all trials and recordings of the chosen experiment. Each experiment is identifiable by a unique number.

A **Test/Trial** is related to a walk of the proband. Each test is characterized by a unique number.

Each **Sensor** has a unique key in the form of [F/S/T/VP] [L/R] or EMG or XYZ, where F - Foot, S - Shank, T - Thigh, VP - Pelvis, L - Left, R - Right, EMG - sEMG, XYZ – accelerometer, e.g. FsL or SR.

3.2 Webpage

A webpage[10] serves the entry point - the graphical user interface - to the GaitAnalysisDataBase. The webpage offers two informative subpages, a download area and three approaches to search data sets via scenarios, probands or experiments.

Tab "Scenarios": all scenarios extended by a table of related experiments are listed.

Tab "Probands": all anonymized subjects, their personal data and a table of scenarios, where they were involved, is presented.

Tab "Experiments": the table of all experiments provides links to individual pages where all datasets sorted by the number of trials and the sensors are listed. Any entry includes the abbreviation of the sensor position, stride characteristics and the number of strides as well as links to the preview and the download of the selected dataset.

3.3 Recordings

Each record consists of two parts: the metadata block, describing the data, and the binary coded data.

3.3.1 Xsens MTw Recordings

Xsens IMUs record acceleration, angular velocity and magnetic rate vectors, as well as the orientation of the sensor. The acquired data were transformed from the sensor related coordinate system into the world coordinate system and gravity compensated.

Each dataset contains the measurements from a single IMU. The metadata block includes: date, proband ID, number of test, sensor position, sensor id, number of columns, number of samples, precision, sampling rate, duration of recording, number of speed levels, scaling factors of acceleration, angular velocity and quaternions.

3.3.2 PLUX Recordings

PLUX units sample up to 8 channels depending on the number and the type of primary sensors. While a sEMG has only one signal, an XYZ sensor has three channels - one for each direction.

Each EMG or XYZ dataset contains the measurements of a single unit. The metadata block includes: date, alias, number of test, type of sensor, number of columns, abbreviations of muscles, number of samples, sampling rate, precision, duration of recording, number of speed levels.

[10] http://gaitanalysis. th-brandenburg.de

3.4 Export and Import of Data Files

Any recording can be downloaded from the specified experiment page.

The names of the data files are transliterated as YYYMMDD_Pnnnn_ttt_XXX_mmm, where YYYYMMDD - date, Pnnnn - proband ID, ttt - trail, XXX - sensor type and , mmm - sensor id, e.g. . 20141029_P0008_001_FsL_125.dat.

All data sets could be downloaded at once if meaningful.

To import the downloaded data files into the MATLAB workspace, two functions are provided.

4 EXEMPLARY APPLICATION

The datasets included in the database were acquired in study and research projects for different objectives. First of all, we – students and lecturers - have learned a lot about walking and gait, about sensors and signal processing, about good practice when conducting experiments with individuals, documenting them, collecting and storing data, and, last but not least, making the data available for public use.

Anyway each series of experiments was originated and motivated by specific questions. Two of them will be presented in the following sections.

One typical testing in gait analysis is the "Catwalk" scenario where the subjects are asked to pass several times a distance at a constant, self-selected pace. The distance depends on the available equipment and space. In standard clinical conditions the subject walks about 10 m in one direction, so that at least 4 normal strides could be observed. If mobile, wearable sensors are used, the distance could be extended to 20 m (indoor) or more (outdoor). In this case the number of observable gait cycles is greater than 10 and an averaging could make sense.

In various studies the subjects are asked to walk "normal, slow and fast", with "self-selected comfortable, reduced or increased velocity", i.e. on three discriminable speed levels what the subject can easily perform, replicate and control. It should be mentioned that there are large differences between the "normal" speeds of persons, because it depends on physiological characteristics, e.g. height, weight, age and gender, and for one subject in dependence of the personal situation (daily routine, walk with friends, shopping.)

4.1 Individual Pace Control

Examples of investigated questions are:

- What velocities are chosen by any individual as comfortable, reduced and increased?
- Is the individual able to control their walking pace, to separate normal, slow and fast, and to replicate them?
- How do the individuals realize the increase of the pace – by increasing the stride length or the cadence or both simultaneously?

Figures 4a and b include two types of images. Above the determined average stride velocities, length and cadence are shown for both the left and the right shank sensors and for each of the trials. Below their frequency distribution is represented in form of histograms added by the mean value (standard deviation).

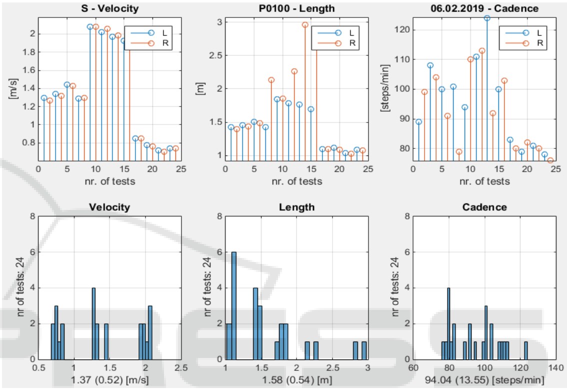

Figure 4a: Individual stride velocity, length and cadence (above) and their histogram (below) of P0100.

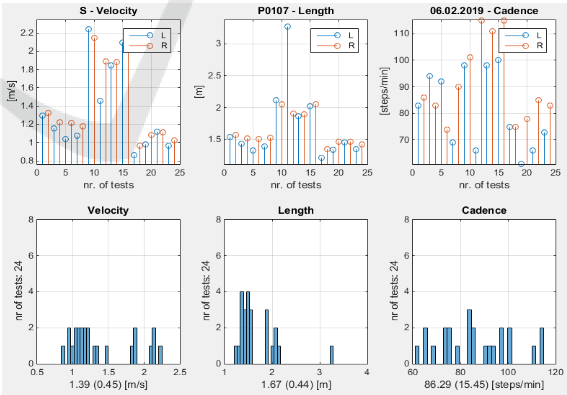

Figure 4b: Individual stride velocity, length and cadence (above) and their histogram (below) of P0107.

Figure 4 presents two different cases:

- In figure 4a the three levels are clearly separated. The change of pace is a result of varying both the length and the cadence was changed.
- Figure 4b presents the case where the normal and slow are on the same level.

4.2 Overall Velocity Distribution

In 2014 and 2015 two groups were involved in the scenario B70Z12, B57E12 and B77E12 “Repetitive Indoor Walking”. The participants were asked to pass four times a distance of about 20 meters at constant pace, first at a self-selected comfortable velocity, then with reduced and last with increased speed. 18 subjects were collected for the test group - experiments 001-018, October/November 2014, age 28 (12), height 178 (9). 10 persons created the control group – experiments 052, 053-062, October 2015, age 24 (9), height 177 (11).

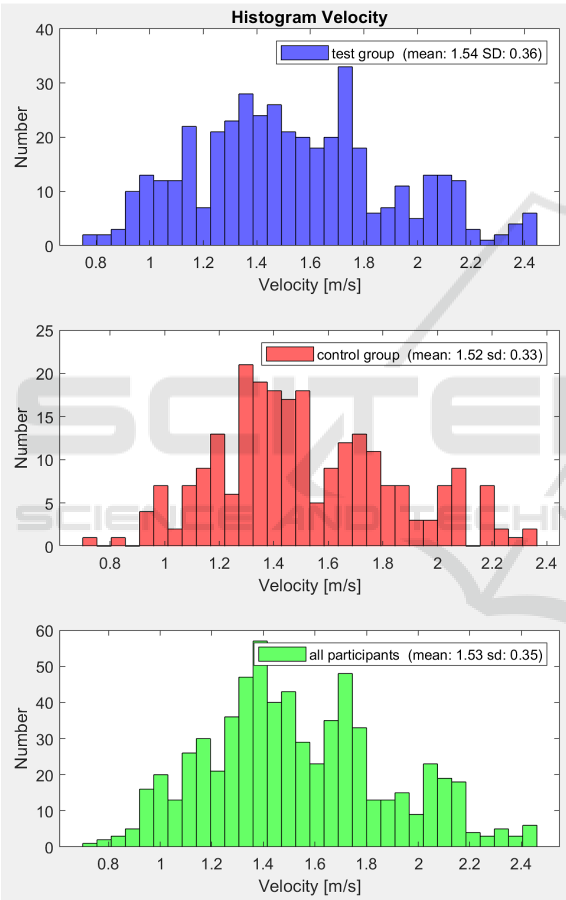

Figure 5: Velocity histogram of the test group (above), the control group (central) and both groups (below).

Seven Xsens MTw sensors were applied: one in the middle of the back, 6 pairwise above the knee, above the ankle and on the shoe. The only difference between the experiments in 2014 and 2015 concerns to the position of the foot sensors: lateral centric in 2014 and on the metatarsus in 2015.

Figure 5 shows the velocity distribution of the test (above) and control group (below) and all together. It could be mentioned that the results (mean value and the standard deviation) are very close. The small difference could be a result of the different positions of the foot sensors. The distance between the foot sensor positioned lateral and the hip is obviously greater than the correspondent distance from the metatarsus (on the top of the foot). It follows that the measured accelerations and the calculated velocities are a bit higher in 2014.

4.3 Dependencies of Gait Parameters on Walking Velocity

There are various ways to investigate the dependency of stride characteristics on the walking velocity. The scenarios of “Repetitive Walking” or “Walking on a treadmill with pre-set speeds or incremental speed profile” could be employed. Here the scenario L70Z01 – “Treadmill with incremental speed profile” was chosen. 7 speed levels run through, including at least 40 seconds periods of stabilized walking, during each trial. The disadvantage of this approach could be the influence of the moving belt on the walking pattern.

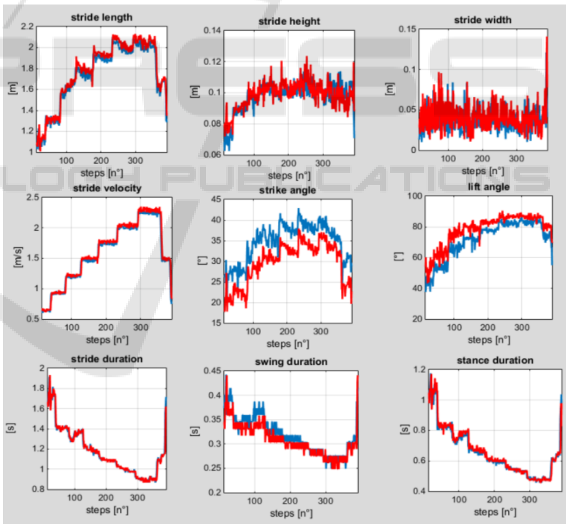

Figure 6: Influence of the treadmill speed on stride characteristics: length, height, width, velocity, strike and lift angle, duration of stride, stance and swing (red – left, blue – right leg).

Figure 6 illustrates the dependency of stride characteristics like stride length, height, width and velocity, strike and lift angle, duration of stride, stance and swing on the numbers of steps for a single experiment (Loose, 2016). The number of executed strides corresponds to the belt velocity which was incremented every 60 seconds by 1 km/h and decremented later every 30 seconds. It increases together with treadmill speed (see subplot "stride velocity"). Obviously stride length, height, strike and lift angle rise with increasing stride velocity, while stride, stance and swing duration descend. A higher stride velocity is achieved by increasing the stride length and shortening the stride duration. The relationship between the stance and swing phases is changing. The stance phase becomes shorter relatively to the swing phase.

5 CONCLUSIONS

This paper presents the GaitAnalysisDataBase, which provides data sets of walking for public use, that could be used to develop and evaluate algorithms, and to investigate different research problems without having to collect own data.

The paper gives a detailed description of the database, its webpage and the used terms (scenario, proband, experiment and trial). An overview about the experimental setup, the acquisition of data, the procedure of experiments, data processing and evaluation is included. Results of exemplary investigations are described in the second part of the paper.

The public database opens up manifold opportunities for research and development tasks as well as for educational projects and studies in the field of gait analysis.

To extend the database including so-called annotation files, providing intermediate results, i.e. detected gait events, duration and length of strides, is still under consideration. The presented results on any experiment page are not intended for comparison, but for classification of the trial.

We would be pleased to see the offer taken up and would appreciate any hint to improve or extend the database. We kindly ask you to cite this paper should you use this database for your publications or the research.

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