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Detection of Physical Activity Types Using Triaxial Accelerometers

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***Background*:** The aim of this study was to validate a triaxial accelerometer setup for identifying everyday physical activity types (ie, sitting, standing, walking, walking stairs, running, and cycling). ***Methods*:** Seventeen subjects equipped with triaxial accelerometers (ActiGraph GT3X+) at the thigh and hip carried out a standardized test procedure including walking, running, cycling, walking stairs, sitting, and standing still. A method was developed (Acti4) to discriminate between these physical activity types based on threshold values of standard deviation of acceleration and the derived inclination. Moreover, the ability of the accelerometer placed at the thigh to detect sitting posture was separately validated during free living by comparison with recordings of pressure sensors in the hip pockets. ***Results*:** Sensitivity for discriminating between the physical activity types sitting, standing, walking, running, and cycling in the standardized trials were 99%–100% and 95% for walking stairs. Specificity was higher than 99% for all activities. During free living (140 hours of measurements), sensitivity and specificity for detection of sitting posture were 98% and 93%, respectively. ***Conclusion*:** The developed method for detecting physical activity types showed a high sensitivity and specificity for sitting, standing, walking, running, walking stairs, and cycling in a standardized setting and for sitting posture during free living.

***Keywords*:** everyday life, accelerometry, inclination, Actigraph GT3X+, Actilife, Acti4

Physical activity is well documented to predict large public chronic diseases like obesity, diabetes, hypertension, stroke, cancer, and metabolic syndrome.[1] Therefore, assessment of physical activity in everyday life has in recent years been subject to considerable interest, and various subjective and objective methods have been developed.[2–4] Subjective methods based on questionnaires and diaries rely on individual memory and interpretation and may suffer from inconsistencies and bias.[5–7] Therefore, objective methods based on measurements of physical activity are attractive; the rapid technological developments have opened for possibilities that did not exist a few years ago. For example, small, lightweight devices capable of sampling and storing raw, triaxial acceleration data for up to a couple of weeks are commercial available.[8] These accelerometers are sensitive to the combined gravitational and dynamic acceleration, which makes it possible to derive both inclinometric information and assess intensity of movements.[9]

Most studies measuring physical activity during everyday life have focused on energy expenditure, which is most often estimated from a single accelerometer worn at the hip.[10–12] However, recent studies have shown independent effects of self-reported physical activity types like sitting, standing, and walking on cardiovascular diseases and mortality.[13–17] Moreover, self-reported excessive time spent sitting is shown to increase the risk of cardiovascular and all-cause mortality among even physically active individuals.[13,14] Therefore, it is of importance to measure different physical activity types during everyday living independently of physical activity energy expenditure.

Lying/sitting and standing postures can be distinguished by a single accelerometer positioned at the waist or hip, but discriminating between sitting and standing is difficult only by means of data from this accelerometer position, because the inclination of the hip does not differ significantly between standing position and upright sitting.[18,19] For this reason some studies have been carried out with 2 or more accelerometer sensors wired to a central data logging unit.[18, 20-24] However, the number of accelerometers and complexity of these systems impede a long-term monitoring in free-living environments. Recently, self-contained accelerometer units that can store raw data for long periods of time have become available, making it more feasible to carry out long-term monitoring using accelerometers on different body positions.[8] Moreover, the ability of researchers to obtain the raw data opens up new possibilities for data

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analysis that were not previously included into the system by the manufacturer.

Commercial accelerometer-based monitors like ActiGraph,[8] ActivPAL,[25] and IDEEA[26] all record information on sedentary/activity behaviors, but with some differences in measurement method, available output parameters and level of details and cost (relative cost ratios approximately 1:2:10). The ActiGraph monitor is worn at the hip and primarily records the activity intensity (eg, sedentary, light, moderate, vigorous) and estimates energy expenditure and counts steps. New versions of the monitor (GT3X) also estimate lying, sitting, and standing postures, although the discrimination between sitting and standing is questionable.[18,19,27] The ActivPAL monitor is designed to be worn (fixed with special adhesive pad) at the thigh and the output includes time spent in sitting/lying, standing, and walking postures and number of steps. The ActivPAL is not able to discriminate between sitting and lying posture. The IDEEA monitor includes 5 sensors taped to the skin of the chest, both thighs and both soles of the feet, all wired to a central datalogger/processing unit attached to a belt. By means of neural network detection the monitor distinguishes between 32 types of postures, gaits (and variants), and outputs several parameters including energy expenditure, steps, etc.

To implement large scale studies of activity behaviors, the measurements systems should be affordable, impose a low participant burden, and able to distinguish among various physical activity types.[28] The ActiGraph monitors are relatively affordable with a low participant burden, but its ability to distinguish among various physical activity types like lying, sitting, standing, walking, walking stairs, running, and cycling has not been investigated previously. To detect these activity types, it is estimated that the thigh would be the most appropriate measuring position; however, data obtained at the hip position might be necessary to detect a lying position.

The aim of this study was to develop a method for identifying everyday physical activity types like walking, running, cycling, walking stairs, standing, and sitting using triaxial accelerometers (ActiGraph GT3X+) worn at the thigh and the hip.

Methods and Procedures

Procedures

The study subjects were asked to perform 2 protocols: 1) a standardized 30 minutes protocol for setting up criteria for detection of several everyday physical activity types and 2) a 9-hour protocol for detection of sitting posture during free living. Both protocols provided the subjects with an ActiGraph GT3X+ accelerometer at the right thigh. During the free-living protocol, the subjects were also fitted with an accelerometer at the right hip and pressure sensors in the hip pockets to detect sitting posture.

Subjects

Seventeen healthy subjects (10 females and 7 males, age 34 ± 11 years, weight 74 ± 14 kg, height 171 ± 14 cm, BMI 25 ± 5 kg/m^2) with mainly office work were included in the study. It was aimed to recruit subjects presenting a normal biological variation according to height and body weight. Criteria of exclusion were severe allergy to band aid, pregnancy and/or fever on the day of testing. The subjects were informed of the general aims of the study and gave a written consent to participate. The experiment was approved by the local Ethics Committee (H-2-2011-047) and conducted in accordance with the Helsinki declaration.

Instrumentation

Accelerometers (ActiGraph GT3X+) recording accelerations in 3 directions with a frequency of 30Hz were used. The dynamic range of the accelerometer is ± 6G (1G = 9.81m/s^2) and accelerations are sampled with a precision of 12 bit and raw data stored in a 250MB memory. The size of the accelerometer is 19 × 34 × 45 mm, weight 19 g, and it is water resistant up to 1 m. The accelerometers were initialized for recording and data downloaded using the manufacturer's software (ActiLife version 5.5).[8]

One accelerometer was fixed by tape (3M, Hair-Set, double sided adhesive tape, and Fixomull, BSN medical) at the right medial front thigh midway between the hip and knee joint orientated with the x-axis pointing downward, y-axis horizontally to the left and z-axis horizontally forward. A second accelerometer was fixed by an elastic belt at the right side of the hip, near the upper point of iliac crest, which is the recommended, standardized position.[10,29] This accelerometer was oriented with the x-axis pointing downward, y-axis horizontally forward, and z-axis horizontally to the right.

For validation of measuring sitting posture during unrestricted free living over several hours, the subjects were provided with a pressure logger consisting of 2 × 2 pressure sensors (force sensitive polymer thick film resistors, 28 mm in diameter, Interlink Electronics) placed in both hip pockets and a data logger (EL-USB-3, Lascar Electronics). The data logger recorded mechanical pressure for a period up to 9 hours with a sampling frequency of 1 Hz. By comparing recordings of the pressure logger and exact time keeping records of sitting, the pressure sensors were found to record sitting posture in a very valid and reliable manner. Both the ActiGraph and the pressure logger are discrete and small, light-weight monitors not interfering with the everyday life of the subject.

Protocol for Detection of Physical Activity Types Under Controlled Conditions

A protocol was performed for setting up criteria for discriminating between 6 different standardized, everyday physical activity types (ie, walking, running, cycling, walking stairs, sitting, and standing). According to this protocol (subsequently referred to as standardized protocol) each subject carried out a supervised, fixed scheme of these physical activity types, each lasting approximately 5 minutes and 30 minutes in total. The protocol aimed at imitating free-living conditions; therefore, walking, running, and cycling were carried out outdoors and in 2 self-paced speeds: "moderate" and "brisk" as inspired by an earlier validation study.[18] The sitting activity was performed by sitting on an ordinary office chair in a computer workplace, and for the standing activity, the subjects were asked to stand still. The exact time of beginning and end of each respective physical activity type was recorded. For this setup, the subjects wore 1 accelerometer at the thigh.

Protocol for Detection of Sitting Posture During Free Living

By means of the standardized protocol, criteria were derived for discriminating between 6 different consistent physical activity types, among them sitting activity. A second protocol was performed to validate the criteria for detecting sitting posture during free living. This set-up used an accelerometer at the thigh, a hip pocket pressure sensor for detecting sitting posture, and an accelerometer at the hip for detecting lying posture. The subjects were instructed to carry out their everyday life during a 9-hour measurement period, which included working hours (mainly office work) and off-duty hours, including travel time on the way home from work. The subjects were asked to fill out a diary, specifying the start and end of working hours, travel time and time spent lying, and if/when it has been necessary to take off the accelerometers during the measurement.

Data Analysis

Data from the thigh accelerometer was analyzed with dedicated Matlab software (Acti4). Initially the accelerometer data were low-pass filtered with a 5 Hz, 4th order Butterworth filter and divided in intervals of 2 seconds with 50% overlap. The 2 seconds length was set to derive roughly stationary average parameters for the interval. This was achieved by setting the interval length to include a few cycles of acceleration data for typical moving activities; for example, for walking, 2 sec would normally include 2–4 steps. For each interval, a set of classification parameters were derived. The mean acceleration $A = (A_x,A_y,A_z)$ and standard deviation $SD = (SD_x,SD_y,SD_z)$ were calculated and the inclination of the x-axis $Inc = acos(A_x/(A_x^2+A_y^2+A_z^2)^{1/2})$. Since the x-axis of the accelerometer is parallel to the thigh axis, the inclination tells the angle between the vertical line and the thigh axis, which is a positive value in the range 0°–180°; therefore, the inclination does not differentiate between forward and backward position of the thigh. To discriminate between level walking and walking stairs a forward/backward angle θ of the thigh was introduced and derived as $\theta = -asin(A_z/(A_x^2+A_y^2+A_z^2)^{1/2})$ yielding a value in the range ± 90°. Note that the Inc (and θ) parameters are calculated from 2-second averaged values of acceleration; so strictly speaking, these parameters only represent true angle values in conditions that can be regarded as static/quasi-static during a 2-second interval. For dynamic conditions such as moving types of activity they do not exactly equal true angle values calculated from instantaneous values of acceleration; however, this is immaterial for the Inc and θ parameters in their role as classification parameters.

For the activity periods included in the standardized protocol setup, a value was calculated for each of the parameters SD_x, SD_y, SD_z, Inc and θ for all 2-second intervals and pooled distributions for all subjects of SD_x, maximum of SD (SD_{max}), Inc, and θ were derived. By means of these distributions, a classification scheme was developed to discriminate between the everyday physical activity types. The effectiveness of the method was assessed by calculating the classification specificity and sensitivity for detection of each physical activity type. The sensitivity is the proportion of measurements correctly identified within the number of measurements actually belonging to that physical activity. The specificity is the proportion of measurements correctly identified within the number of measurement not belonging to that physical activity type.

For the free-living measurements, the classification parameters were calculated and periods with sitting posture were identified by the classification method developed via the standardized protocol setup and by the pressure logger recordings. Taking the pressure logger as reference, the capability of the 2 accelerometers to detect sitting posture was assessed for each subject by calculating sensitivity and specificity.

Periods in which the accelerometer was not worn were identified and excluded from the analysis. It was observed that taking off an accelerometer and putting it on an office table or alike, normally results in considerable accelerations. Therefore, the following criteria for detection of a not-worn state were used: All periods longer than 60 minutes without movement of the accelerometer was always considered not-worn. Periods less than 10 minutes without movement[I] were not regarded as not-worn. Periods between 10 and 60 minutes was determined as not-worn if $SD_x+SD_y+SD_z > 0.5G$ for any second during a 5-second interval immediately before the period without movement (raw, unfiltered data were used for this SD calculation).

Data from the hip accelerometer was analyzed by the ActiLife software version 5.5, which includes estimation of periods with standing, sitting and lying posture and not-worn periods: According to this software, a standing posture is detected if the inclination of the accelerometer's vertical axis is less than 17°. The posture is considered sitting if the inclination is between 17° and 65° and lying if the inclination is above 65°. The ActiLife software detects periods in which the accelerometer is not worn by utilizing specific criteria for prolonged periods without acceleration and the recorded orientation of the accelerometer. This way of detection "not-worn" periods was compared with the above method.

Results

Protocol for Detection of Physical Activity Types Under Controlled Conditions

The measurements of the thigh accelerometer were divided into sections corresponding to the recorded start and stop times of the physical activity types for each subject. Then the distributions of the classification parameters were derived for these sections. The pooled distribution of standard deviation and inclination are shown in Figure 1 and 2. It appears that there is hardly any overlap between the distributions of inclination during cycling and the activities horizontal walking and walking stairs. For sitting and standing, the distributions are even more distinctive. Also distributions of standard deviation in vertical direction (SD_x) for running and walking are sparsely overlapping. The optimal threshold for discriminating between cycling and walking stairs by means of inclination was determined to be 24°. Similarly, the optimal values for discriminating by means of SD_x between running and walking and between sitting/standing and the other activities were determined to be 0.72G and 0.1G, respectively. These values were initially set up by exploring the distributions in Figure 1 and 2. The pooled distributions of the forward/backward angle θ for walking/running and walking stairs did not show such clear cut separation, so the discriminating procedure could not be based on a single value of θ, which could serve as a common threshold for discrimination between walking/running and walking stairs for all subjects. However, examining the set (N = 17) of individual distributions of θ, it appeared that an individual threshold might yield a satisfactory discrimination. For each subject a discrimination angle θ_d was derived as $\theta_d = k + \theta_m$, where k is a constant and θ_m is the median value θ for $\theta < 5°$. This was a way to compensate for small differences in the basic inclination caused by individual thigh shapes. An optimal value of the constant k was k = 4.5° and determined as an average value derived by a 16-fold leave-one-subject-out cross-validation procedure in which the other threshold values parameters where fixed (ie, 24° for discriminating between cycling and walking stairs, 0.72G for discriminating between running and walking, etc.). To reduce sporadic misclassification, median filtering was performed with a window size of 29 seconds for cycling and 9 seconds for the other activities. The median filtering improves the overall classification but removes occurrences of short, isolated physical activity types. For example, a walking period lasting less than 5 seconds would not be recognized if surrounded by longer periods of standing still.

The final classification scheme is visualized by the classification tree illustrated in Figure 3. Because periods not covered by the 6 predefined physical activity types occur during everyday living, the classification scheme included a leftover-category, defined as "Move." These leftover-periods match a standing posture including small movements without regular walking. Sensitivity and specificity for discriminating between the physical activity types, sitting, standing (still), walking, running, walking stairs, and cycling are shown in Table 1. It appears that with exception of walking stairs, the sensitivity is 99%–100%. For walking stairs, some misclassification occurred (ie, some periods of walking stairs were classified at horizontal walking).

Protocol for Detection of Sitting Posture During Free Living

The measurement series yielded 140 hours of simultaneous recording by the hip pocket pressure logger and the thigh and hip accelerometers. Figure 4 depicts an example of an 8-hour recording showing the classification of physical activity types achieved by the pressure logger and accelerometers.

Table 2 shows the sensitivity and specificity of the 2 accelerometers to detect sitting posture for the 17 subjects, taking the pressure logger as reference. It appears that the thigh accelerometer was more precise in detecting sitting posture than the hip accelerometer. Average time not worn, according to the ActiLife software, was 5% whereas the procedure used in this study resulted in 0.5% time not worn.

Discussion

The purpose of this study was to validate a triaxial accelerometer setup for identifying everyday physical activity types. For this purpose, the subjects performed several standardized physical activity types and 9 hours free living with 1 accelerometer at the thigh and another at the "standard" position at the hip.

The main finding was that with the accelerometer attached to the thigh, it was possible to discriminate between several standardized physical activity types (sitting, standing, walking, running and cycling) with a very high (~99%) sensitivity and specificity. For walking stairs, the specificity was very high (100%), but with a slightly lower sensitivity (95%). Furthermore, during unrestricted conditions of free living, the thigh accelerometer showed high ability to detect sitting posture with respect to the pressure logger located in the hip pockets.

The capability to detect sitting posture was somewhat lower during unrestricted free living compared with the standardized condition for shorter periods of time. This is not surprising since long-term recordings would include nonstandardized postures naturally found during off-duty periods like squatting or kneeling. These and some other postures would typically be classified as a standing posture by the pressure logger. Although the pressure sensors fixed at the hip pockets are very likely to be activated during sitting, it cannot be ruled out that some individual sitting postures could be undetected by the pressure logger, suggesting that the real specificity may potentially be even higher than 93%.

In the long-term measurements, some periods were classified as "moving" (ie, leftover periods that match a standing posture including small movements without

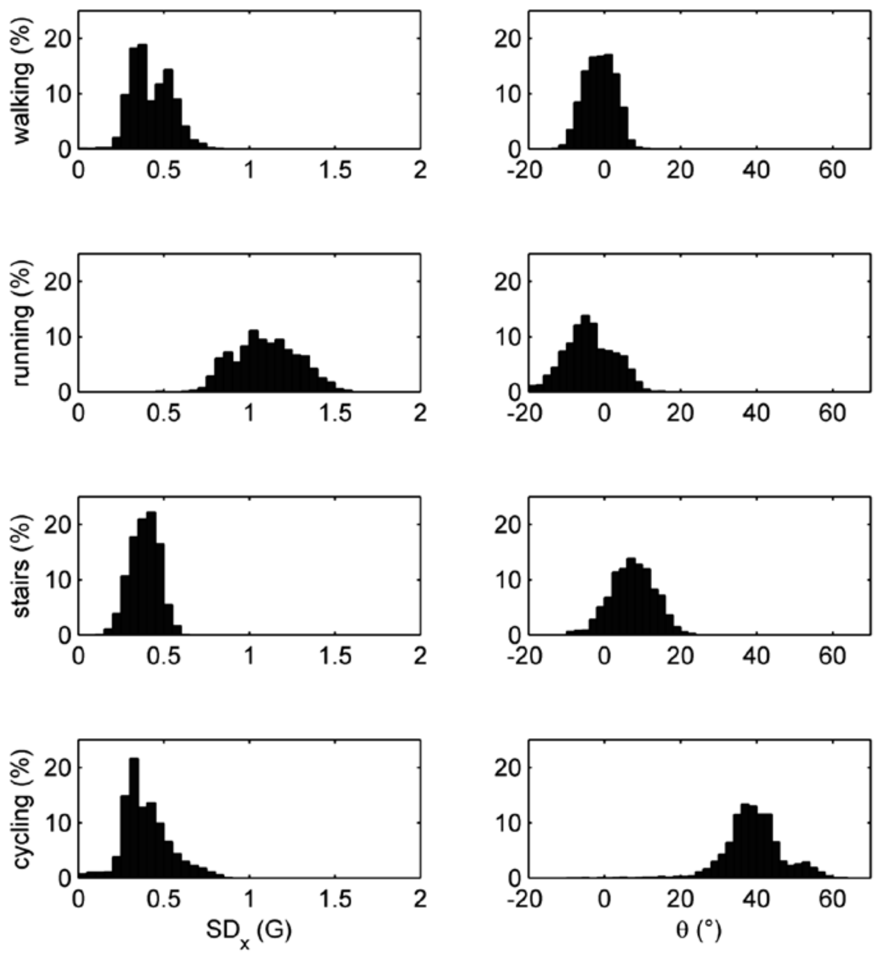

Figure 1 — Distributions of the standard deviation of acceleration in vertical (x-axis) direction (SD_x) and distributions of the forward/backward angle (θ) during 4 standardized physical activity types (horizontal walking, running, walking stairs, and cycling) for all subjects derived from the accelerometer attached to the thigh. Unit on the vertical axis is percentage of total number of measurement (2-second intervals). The units on the horizontal axes are the gravitational acceleration G (1G = 9.81 m/s^2) and degree (angle) for the left and right side plots, respectively.

ordinary walking). An upright posture without regular walking could therefore be classified as standing still or making small movements. This differentiation between standing still and standing while making small movements seems justified, since from an ergonomic point of view, immobile, standing working postures may be unfavorable.[16]

By including a hip accelerometer, lying posture was added to the previous identified physical activity types. In this study, lying posture was defined as an inclination of the hip accelerometer above 65°, a threshold also used by the ActiLife software; however, some subjects occasionally during the work time performed their sitting posture somewhat lying-like, resulting in a classification as lying. This indicates that the optimal inclination threshold for lying might be higher than 65°.

The ActiLife software was not successful in discriminating between sitting and standing postures, which shows that it is difficult to make this differentiation only by means of the inclination of an accelerometer at the hip. During the working hours, some subjects were sitting still for prolonged periods, causing periods to be classified as inclinometer not-worn by the ActiLife software (Figure 4). By applying an alternative rule, this type of misclassification was successfully avoided.

The number of subjects in this study (n = 17) is limited, and within free-living conditions, the method was only validated for detecting the sitting posture. From the very high precision achieved in the standardized, short-term test, however, it is likely that the method will be adequate for detecting the other physical activity types during free-living conditions. Using 2 accelerometers complicates the measurement procedure and increases the risk of errors during the recording periods. The accelerometers are small, however, and can be worn during all everyday activities during 24 hours of day, which were not possible previously, since the accelerometers were not water resistant and wireless.

The method for detection of everyday physical activities presented in this study provides accuracies comparable with results reported for the IDEEA and ActivPAL

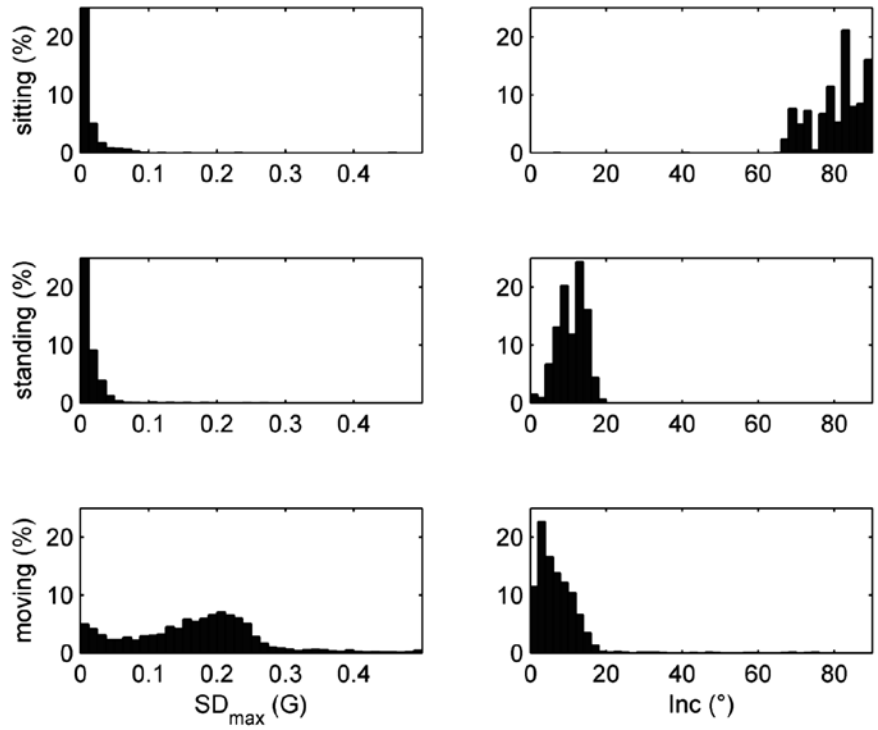

Figure 2 — Distributions of the maximal standard deviation of acceleration [$SD_{max} = max(SD_X,SD_Y,SD_Z)$] and the distributions of inclinations (Inc) during sitting, standing still and "moving" for all subjects derived from the thigh accelerometer. The activity "moving" is a "left-over activity" not independently defined in which the vertical accelerations are below the threshold for the physical activity types involving body movement (cycling, walking, or running) but above the threshold for standing still. Unit on the vertical axis is percentage of total number of measurement (2-second intervals). The units on the horizontal axes are the gravitational acceleration G ($1G = 9.81\ m/s^2$) and degree (angle) for the left and right side plots, respectively.

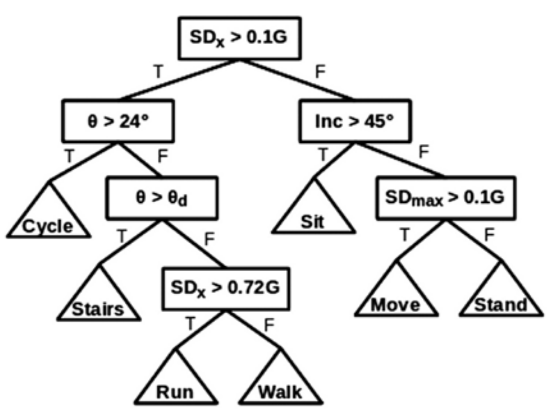

Figure 3 — Decision tree depicting the algorithm for classifying the physical activity types by the thigh accelerometer recording (decision node represented by boxes and end nodes [physical activity types] by triangles). SD_x: vertical standard deviation; SD_{max}: maximum standard deviation in 3 directions; Inc: inclination of thigh; θ: forward/backward angle of thigh (θ_d individual threshold angle). Branches to the left represent a true case (T) and to the right a false case (F).

Table 1 Sensitivity and Specificity of a Discrimination Method for Classifying Physical Activity Types in Standardized Field Trials

Activity	Sensitivity (%)	Specificity (%)
Sitting	99.9	100.0
Standing	100.0	100.0
Walking	99.4	99.7
Running	98.7	99.9
Stairs	95.3	100.0
Cycling	99.9	100.0

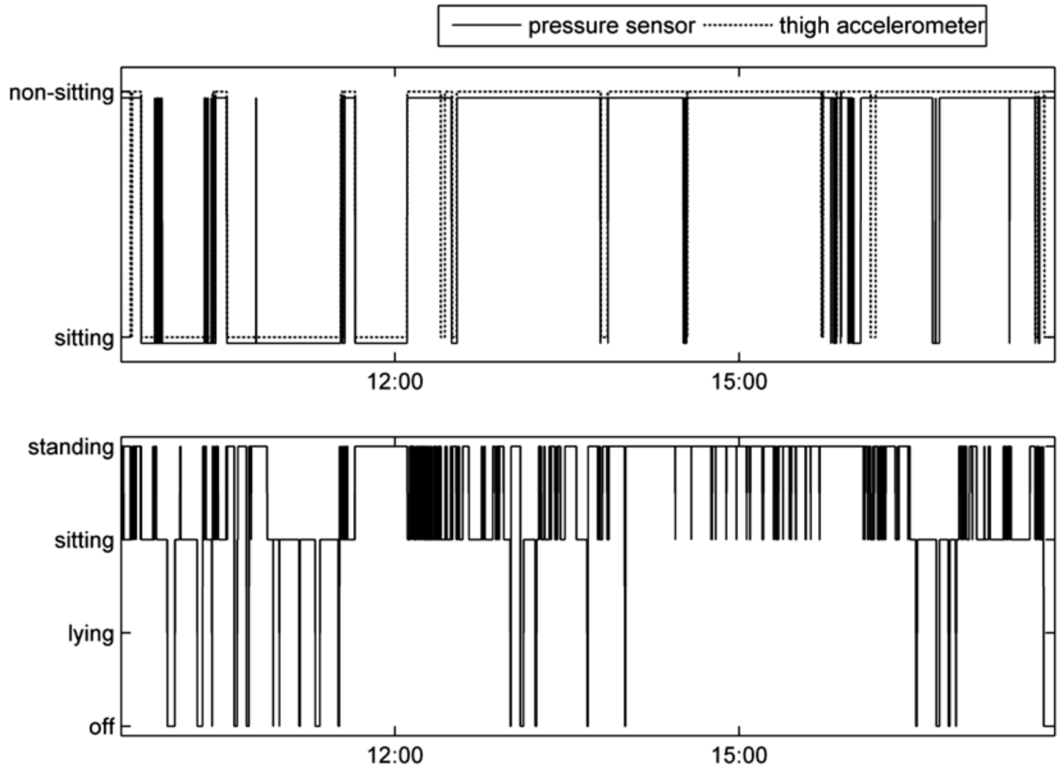

Figure 4 — Example of an 8-hour recording for 1 subject showing the classification of physical activity types by the pressure sensors in the hip pockets and Actigraph accelerometers. Top figure: Pressure sensor and thigh accelerometer recording. The pressure logger estimates sitting posture by the pressure sensors in the hip pockets. A sitting posture is detected by the thigh Actigraph accelerometer by means of the derived inclination (sitting defined by inclination > 45°). Bottom figure: ActiLife analysis of hip accelerometer recording. The commercial ActiLife software detects the postures standing, sitting, lying, and accelerometer not-worn (off). It appears that for several short periods, an "off state" was detected. However, the subject wore the accelerometer all the time (sitting still and working with a computer).

Table 2 Sensitivity and Specificity (Mean, SD; n = 17) of Sitting Time During 9 Hours of Unrestricted Free Living Assessed by the Accelerometer Attached at the Thigh and the Hip Compared With Sitting Time Assessed by Pressure Sensors in the Hip Pockets (Reference Method)

Accelerometer	Sensitivity (%)	Specificity (%)
Thigh	98.2 (1.9)	93.3 (6.0)
Hip	72.8 (26.6)	58.0 (20.4)

systems in other studies. For the advanced and expensive IDEEA system were found overall accuracies for sitting, standing, walking, and walking stairs in the range 98.2%–99.7% in a standardized laboratory setup.[21] Similarly, the ActivPAL system achieved sensitivities for detection of sitting, standing and walking of 97.3%–99.7%.[30] Although some differences exist regarding output parameters of the monitor systems and also in the methods of validation, which make direct comparison difficult, the results in this study obviously match these reported results.

Self-reported information about physical activity types has shown a high predictive value for cardiovascular disease and mortality.[13–17] Because of the recessive reliability and validity of self-reported physical activity types,[5,6,31] the need for objective measurements of physical activity types during free living are well acknowledged. Measurements with ActiGraph GT3X+ enable recordings during every day life for several days. By applying the method in this paper, it is possible to objectively measure physical activity types during several days of free living. Therefore, it now seems possible to investigate the association between objectively measured physical activity types and risk for cardiovascular and metabolic related disease in prospective cohort studies. It is further noted that the present approach might be used for improving of calculation of energy expenditure when the type of activity of certain time periods is known.

To conclude, the study showed that by recordings with a triaxial accelerometer (Actigraph GT3X+) at the thigh, it was possible with high accuracy to detect several physical activity types (ie, sitting, standing, walking, running, walking stairs, and cycling). By adding an accelerometer at the hip, discrimination between lying and sitting during free living was included. The developed method has a significant potential for objective measurements of everyday physical activity type during several days.

Notes

[I] When the GT3X+ unit detects no change in acceleration for any of the 3 axis during 10 seconds, it enters a Low Power Mode during which the acceleration is sampled once every second, and as long as no change is detected, it stays in this mode. When a change is detected, the device enters the normal sampling state again (30 Hz in this study). The occurrences of Low Power Mode were used to select periods "without movement."

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