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Activity Level Classification Algorithm Using SHIMMER™ Wearable Sensors for Individuals with Rheumatoid Arthritis

Emma Fortune, Marie Tierney, Cliodhna Ni Scanaill, Ala Bourke, Norelee Kennedy, and John Nelson

Abstract— **In rheumatoid arthritis (RA) it is believed that symptoms associated with the progression of the disease result in a reduction in the physical activity level of the patient. One of the key flaws of the research surrounding this hypothesis to date is the use of non-validated physical activity outcomes measures. In this study, an algorithm to estimate physical activity levels in patients as they perform a simulated protocol of typical activities of daily living using SHIMMER kinematic sensors, incorporating tri-axial gyroscopes and accelerometers, is proposed. The results are validated against simultaneously recorded energy expenditure data and the defined activity protocol and demonstrate that SHIMMER can be used to accurately estimate physical activity levels in RA populations.**

I. Introduction

RHEUMATOID arthritis (RA) is a chronic systemic inflammatory disorder which primarily affects synovial joints [1]. Inflammation of the synovial membrane that lines the joints and tendon sheaths causes the joints to become swollen, tender, warm and stiff, particularly following prolonged periods of inactivity. These manifestations of the disease limit the movement of the affected joints, and are believed to result in increased physical inactivity of the affected patients [1]. Physical activity is defined as any bodily movement, produced by skeletal muscles, that requires energy expenditure [2, 3]. Physical inactivity is an independent risk factor for chronic disease and is estimated to cause 1.9 million deaths world-wide every year (WHO). As inactivity in patients suffering from RA exasperates stiffness and pain in the joints, it is imperative that sufferers maintain healthy physical activity levels despite the movement limitations induced by the disorder and it has been suggested that high intensity resistive training should play a role in disease management [4]. Furthermore, RA patients have an approximate 50% higher mortality rate than the general population [5] due mostly to cardiovascular disease (CVD) [6, 7]. Regular physical activity has been associated with health improvements in a number of populations and a decreased incidence of CVD has been reported in more physically active subjects [8].

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E. Fortune and C. Ni Scanaill (email: Cliodhna.Ni.Scanaill@intel.com) are with the Intel Health Research and Innovation Group, Leixlip, Co. Kildare, Ireland and the TRIL Centre.

M. Tierney (e-mail: Marie.Tierney@ul.ie) and N. Kennedy are with the Dept. of Physiotherapy and A. Bourke and J. Nelson are with the Dept. of Electronic and Computer Engineering, University of Limerick, Ireland.

The most common measures of physical activity are step counts and energy expenditure [9]. The "gold standard" criterion for measuring energy expenditure in free-living situations is Doubly Labeled Water (DLW) [10], however this method presents a number of disadvantages such as its high cost, need for trained personnel and the long time required for energy expenditure measurement. Calorimetry is also considered a criterion method of energy expenditure measurement [11]. Energy expenditure is estimated based upon measurement of heat emitted by the body with direct calorimetry [12] and from O_2 (oxygen) consumption and CO_2 production with indirect calorimetry [13].

A number of studies have used body-worn sensors in to characterize different postures, motions and thus activities in both healthy and diseased subjects [14, 15]. However, these methods have not been validated in the RA population. This team recently developed a SHIMMER (Sensing Health with Intelligence, Modularity, Mobility and Experimental Re-usability) (Realtime Technologies, Dublin, Ireland) gyroscope-based activity level monitor using step count estimation in this population. While the use and analysis of SHIMMER demonstrated a high level of accuracy for step count estimation, the issue with this method being used for activity level monitoring is that the size or force of the step is not taken into consideration and therefore household chores where a high number of small steps are taken could be considered as a higher level activity than one such as stair climbing for a shorter amount of time. Furthermore, activities of lower intensities, i.e. those with small force/ size steps, were not accurately represented.

The aim of this study was to develop and validate a more accurate accelerometer- and gyroscope-based algorithm capable of estimating activity levels in RA patients.

II. Methods

A. Data Set

Kinematic gait and energy expenditure data were acquired from 14 (8 M, 6 F) patients as they performed a 75 minute standardized routine consisting of lifestyle and housework activities in the Department of Physiotherapy in the University of Limerick. Data from two subjects were discarded due to issues with the equipment. The patients were recruited from the rheumatology outpatients' clinic of the Mid-western Regional Hospital, in Limerick, Ireland and each patient had a confirmed diagnosis of RA according to the American College of Rheumatology criteria and was over 18 years of age. They were all on a stable steroidal and disease modifying anti-rheumatic drug regime in the previous three months and were ambulatory independently or with the assistance of one unilateral aid. At the time of evaluation, the mean age and weight of the participants were 64.43 ± 6.8 yrs and 77.3 ± 12.0 kg respectively. Each subject provided written informed consent and completed a Physical Activity Readiness Questionnaire (PAR-Q) before participating.

B. Data Acquisition

Kinematic data were captured from each patient as they performed 8 different activities of daily living using a SHIMMER kinematic sensor attached at the thigh. The SHIMMER is a lightweight, low-power, wirelessly enabled sensor platform which can be utilized for body-worn applications. In this study, each kinematic sensor incorporated a tri-axial accelerometer on the base board with an add-on tri-axial gyroscope daughter board and was programmed to sample each axis at a rate of 51.2 Hz using custom developed TinyOS firmware.

Energy expenditure data were simultaneously acquired by fitting subjects with the Oxycon mobile indirect calorimetry system (CareFusion, CA) with facemask. This acted as the criterion measure for energy expenditure and was used to validate the algorithms applied to the gyroscope and accelerometer data. The Oxycon mobile is a light battery operated portable ergospirometry system that is mounted to the body via a vest. It records the data on a breath-by-breath basis and is collected through a facemask or mouth piece and sent wirelessly to a host computer [16].

C. Protocol

The standardised routine of various lifestyle and housework activities performed by the subjects included: (1) dressing, (2) walking, (3) reading, (4) washing and drying dishes, (5) stair climbing, (6) writing, (7) cleaning and (8) folding laundry. Activities were performed in the order outlined to allow activities of higher intensity to be followed by activities of lower intensity with each activity lasting 10 minutes with the exception of the stair climbing task which lasted for 5 minutes. The activities in the protocol were based on those included in the Evaluation of Daily Activity Questionnaire (EDAQ) as used by Nordenskiold *et al.* [17] in individuals with RA. It also encompassed activities exhibiting a range of varying metabolic equivalent (MET) intensities [18] and was based upon previous validation studies on the Actiheart physical activity monitor [19]. The activity protocol was divided into Class A (3 - 5 METS) (walking, stair climbing and cleaning tasks), Class B (2 - 3 METS) (dressing, washing and drying dishes and folding laundry) and Class C (1 - 2 METS) (reading and writing tasks) intensity activities [18].

D. Signal Processing

All post processing and analysis was carried out off-line using MATLAB (Version 7.9. Mathworks, Natick, MA, USA). The raw accelerometer and gyroscope data were calibrated to derive the acceleration and angular velocity vectors with respect to the sensor unit coordinate axis [20], Fig. 1. The data were filtered using a moving average root-mean-square (RMS) algorithm using 30 s windows to compare them to the average energy expenditure every 30 s. Results from subject 8 are presented in Figs. 1-3 and Tables 1-2 as they showed the greatest accuracy for activity classification out of all the subjects. Sections 1-8 in Figs. 1-3 represent the 8 activities outlined in the protocol.

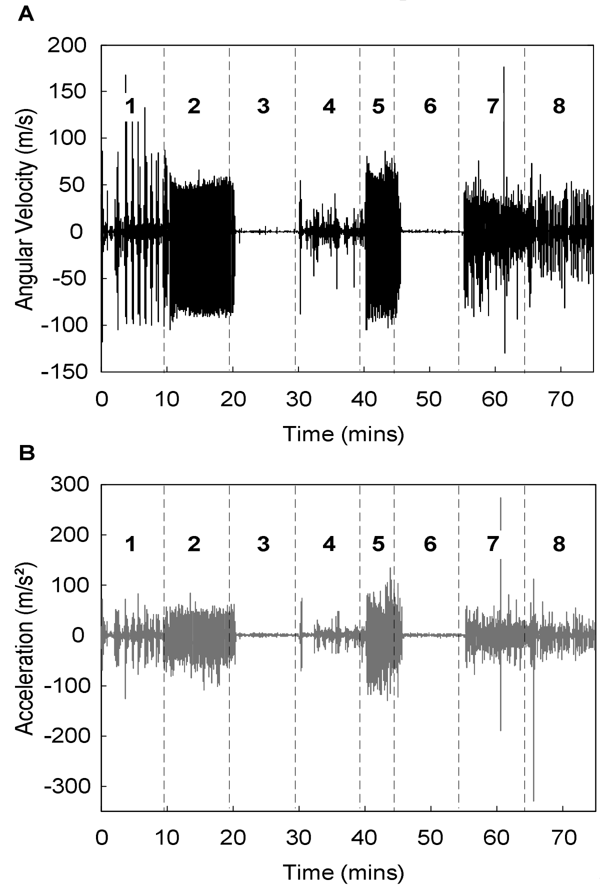

Fig. 1 Example from subject 8 of (A) Calibrated gyroscope signal (black) and (B) calibrated accelerometer signal (grey) in the antero-posterior direction.

E. Activity Level Classification

The activity level was estimated for each signal by classifying Class A activities as 50% of the maximum recorded signal parameter and higher, Class B activities as 20-50% of the maximum recorded signal parameter and Class C as 3.3-20% of the maximum recorded signal parameter. Less than 3.3% of the maximum recorded signal parameter was considered to represent no movement. These thresholds were chosen for optimal accuracy in intensity level estimation.

F. Statistical Analysis

The statistical analyses were performed using SPSS version 16.0. Intraclass correlation (ICC) (2,1 two way random effects model, single measure reliability) was used to compare moving average RMS estimations from gyroscope and accelerometer data to energy expenditure data. Similar analysis was used to compare activity level estimations to those defined by the activity protocol.

III. Results

The average RMS amplitude values of the antero-posterior angular velocity and acceleration and the metabolic energy expenditure recorded from subject 8 are presented in Fig. 2. The average RMS acceleration and angular velocity values showed high correlations between them and with the energy expenditure data across all subjects, Table 1.

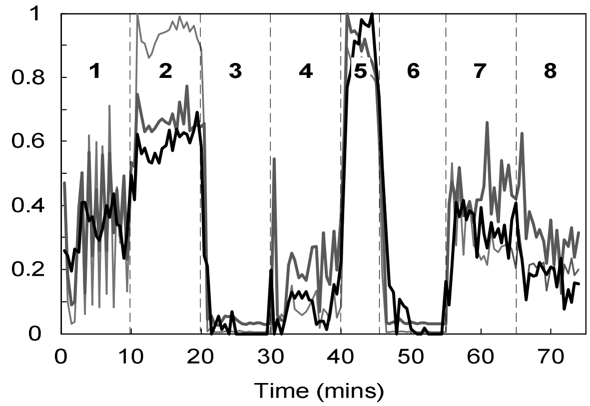

Fig. 2 Example for subject 8 of average root-mean-square values for every 30 s for antero-posterior angular velocity (light grey), antero-posterior acceleration (dark grey) and energy expenditure (black).

The activity levels estimated from antero-posterior angular velocity and acceleration recorded from subject 8 are presented in Fig. 3. The overall classification of each activity was determined by estimating the average RMS amplitude value for the duration of each activity and determining where it lay between the previously defined percentages of RMS amplitude, Table 2. The activity classes estimated from accelerometer data showed a greater accuracy with those defined by the activity protocol than those estimated from gyroscope data, Table 3. Classification of walking and climbing stairs activities had the highest accuracy from both accelerometer and gyroscope data while activities such as sitting reading and writing, washing dishes, dusting and folding laundry had the lowest.

TABLE I
CORRELATION BETWEEN ENERGY EXPENDITURE, AND AVERAGE RMS ANGULAR VELOCITY AND ACCELERATION

Activity	ICC Coefficient	95 % CI
Energy Expenditure - Gyroscope	0.882	0.872 → 0.892
Energy Expenditure - Accelerometer	0.799	0.782 → 0.815
Gyroscope - Accelerometer	0.876	0.865 → 0.886

Intraclass correlation (ICC) coefficient and 95% confidence interval (CI) between energy expenditure, angular velocity and acceleration.

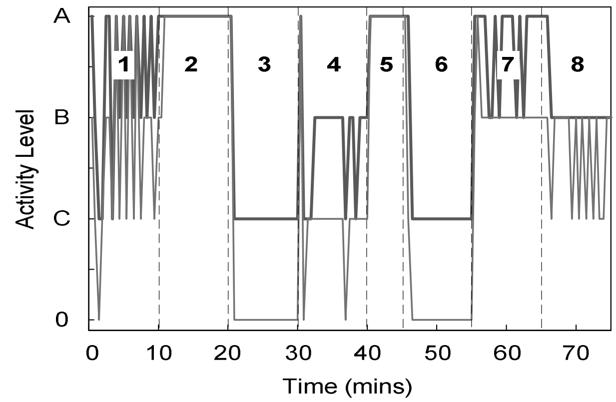

Fig. 3 Example from subject 8 of activity levels for every 30 s for gyroscope (light grey) and accelerometer (dark grey) data.

IV. Discussion

Activity levels are usually estimated using step counts and energy expenditure data. However, step counts do not provide an entirely accurate measurement of activity as the size and force of steps are not taken into consideration, while energy expenditure measurement methods are either costly or unsuitable for home deployment. Furthermore, the energy expenditure measurement methods suitable for home deployment have not been validated in the RA population. For this reason, an activity classification algorithm was developed to analyze both gyroscope and accelerometer signals recorded from 14 RA patients during eight simulated activities of daily living.

TABLE 2
ACTIVITY CLASSIFICATION

Activity	Class	Class (from Gyroscope)	Class (from Accelerometer)
Dressing	B	B	B
Walking	A	A	A
Sitting reading	C	No movement	C
Washing dishes	B	C	B
Stairs climbing up and down	A	A	A
Sitting writing	C	No movement	C
Dusting	A	B	A
Folding laundry	B	B	B

Comparison of activity level classification obtained from analysis of the gyroscope and accelerometer data to those defined by the activity protocol. Example for subject 8 for each of the eight activities performed.

The higher percentage of accuracy in classifying walking and climbing stairs activities compared to the other activities in the protocol, Fig. 3 and Tables 2 and 3, is partly due to the positioning of the SHIMMER on the thigh and walking and climbing stairs activities involving mostly leg movement rather than arm movement. The percentage ranges of the activity level thresholds used in this study result in Class A activities having the highest probability of accurate classification. The high percentage of accuracy in estimating the correct activity level from accelerometer data, Table 3, is consistent with the strong correlation observed between the average RMS amplitude of the accelerometer signals when compared to energy expenditure data across all patients over all activities, Fig. 2 and Table 1. The higher percentage of

TABLE 3
ACCURACY OF ACTIVITY CLASSES ESTIMATION

Activity	Manual -> Gyroscope	Manual -> Accelerometer
	% Accuracy	% Accuracy
1. Dressing	83.33	83.33
2. Walking	100.00	100.00
3. Sitting reading	0.00	66.67
4. Washing dishes	8.33	66.67
5. Stairs climbing	100.00	100.00
6. Sitting writing	0.00	58.33
7. Dusting	0.00	33.33
8. Folding laundry	16.67	91.67
Activities 1 - 8	38.54	75.00

Percentage accuracy between activity levels estimated from gyroscope and accelerometer data and those defined by the activity protocol across all subjects for each activity performed.

accuracy in estimating the activity from accelerometer when compared to gyroscope data, Table 3, may be due to gyroscopes measuring rotation only while accelerometers measure both rotational and translational acceleration making accelerometers more suitable for activity level classification. This is particularly evident in activities involving lower leg and higher arm movement. Another advantage of using accelerometers over gyroscopes is that they use less battery power and are therefore more suitable for home deployment studies.

Although the algorithm estimates activity levels from accelerometer data with a high level of accuracy, there are a number of important limitations associated with this study which must be considered. Participants did not complete activities at intensities of 6METS or higher (vigorous activity) [18] due to the increased cardiovascular risk of RA patients and as testing was taking place away from hospital environment. However it seems reasonable to assume that due to physical disabilities experienced by RA patients, vigorous activity would not be undertaken in free living situation. As this was a simulated protocol of activities of daily living, this method may not be valid for free living use in the RA population. Nonetheless, the results from this study suggest that SHIMMER accelerometer sensors can be used to accurately determine activity levels in the RA population, using the algorithm presented here, in a simulated protocol and remains to be tested in free living. The activity level classification algorithm presented here offers the potential for applications in real time activity level monitoring and classification with the used of additional SHIMMERS on the arm and lower back.

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