Quantitative and Qualitative Assessment of Assisted Strength Exercising

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Abstract— **Human motion detection and tracking systems, which are not video camera based, are becoming more and more popular in rehabilitation, sportsmen tracking or elderly monitoring. The most commonly used motion sensors in these systems are accelerometers and gyroscopes, which are used along with other sensors as a part of wearable wireless body area network (WBAN). In this work we present an algorithm for closed-loop assisted exercising based on Finite State Machine (FSM). The algorithm can be used either for rehabilitation purposes or physical exercise training. As inputs, the algorithm uses real time signals acquired from an accelerometer and a gyroscope of a sensor node in a WBAN. For testing purposes, signals were recorded from 13 healthy subjects during three different strength training exercises (lateral raise, inner-bicep curl, and seated shoulder press) while the sensor node was attached on the wrist of a subject's dominant arm. Qualitative and quantitative assessment of the accelerometer and gyroscope signals was made. Results of tests confirm that assisted exercising using on-line feedback enable more precise movement control closer to prescribed pattern in time and intensity. The proposed FSM based algorithm is suitable for implementation on embedded systems. One of the potential applications of the proposed algorithm is in e-health systems such as HeartWays system providing advanced solutions for supporting cardiac patients in rehabilitation.**

Keywords— **assisted exercising, physical training, rehabilitation, health management, finite-state machine.**

I. INTRODUCTION

In recent years, the detection of body posture and motion received a growing interest for their application in sports, rehabilitation, military, elderly monitoring and other assisted living application [1-4]. The improvements of wireless technology and availability of low-cost MEMS (Micro-Electro-Mechanical Systems) sensors enabled the creation of wireless body sensor networks. In a typical wearable Wireless Body Area Network (WBAN) setting, a patient wears some sensors that form an on-body sensor network, while an off-body base station registers data collected by the WBAN. The most commonly used sensors for human motion detection and tracking, apart from cameras, which are not the topic here, are accelerometers, gyroscopes and magnetometers.

WBANs that have sensors for body posture and activity have great potential in many medical applications such as monitoring of physical therapy for patients who have suffered a stroke, joint replacements, brain injury etc. or for the monitoring of rehabilitation after myocardial infarction where various strength exercises are important part of the rehabilitation program. The purpose of using a WBAN is to improve health care quality and efficacy, and also to reduce health assistance costs since therapy effectiveness can be evaluated remotely.

We have developed a WBAN for continuous personalized monitoring of basic physiological parameters (ECG, respiration rate and body temperature) which also includes motion detection and assisted exercising capability [5]. The aim of our system is to enhance the effectiveness of rehabilitation of patients for whom exercises are indicated (e.g. diabetic patients, cardiac patients etc.) or to enhance the effectiveness of sportsmen training. The system can also support early stage detection of abnormal conditions (e.g. arrhythmia) and thus prevent more serious consequences. Additionally, real-time critical health monitoring implemented in the system can provide professionals with life-important information and reduce the risk of further complications. The system architecture is described in our previous publication [5]. Briefly, WBAN is composed of sensor nodes based on LPC1347 microcontroller. As motion sensors, we used three axis accelerometer (ADXL345) and three axis gyroscope (L3G4200D). The sensor node also has magnetometer (HMC5883L), ECG amplifier, wireless communication module, external memory (microSD card), battery and some auxiliary circuitry.

In this paper we focus on the part of the system which provides closed-loop assisted strength exercising. Closed-loop exercising enables simultaneous continuous recording of physiological parameters and real-time assessment of the quantity and quality aspects of physical activity. Efficient closed-loop assessment is considered very important in order to achieve full potential of rehabilitation or training.

II. CONTROL LOGIC FOR ASSISTED EXERCISING

For the development of control logic for assisted exercising on a wireless sensor node we have chosen the finite-state machine (FSM) model because of its adequate computational power and memory, and simple implementation on an embedded system.

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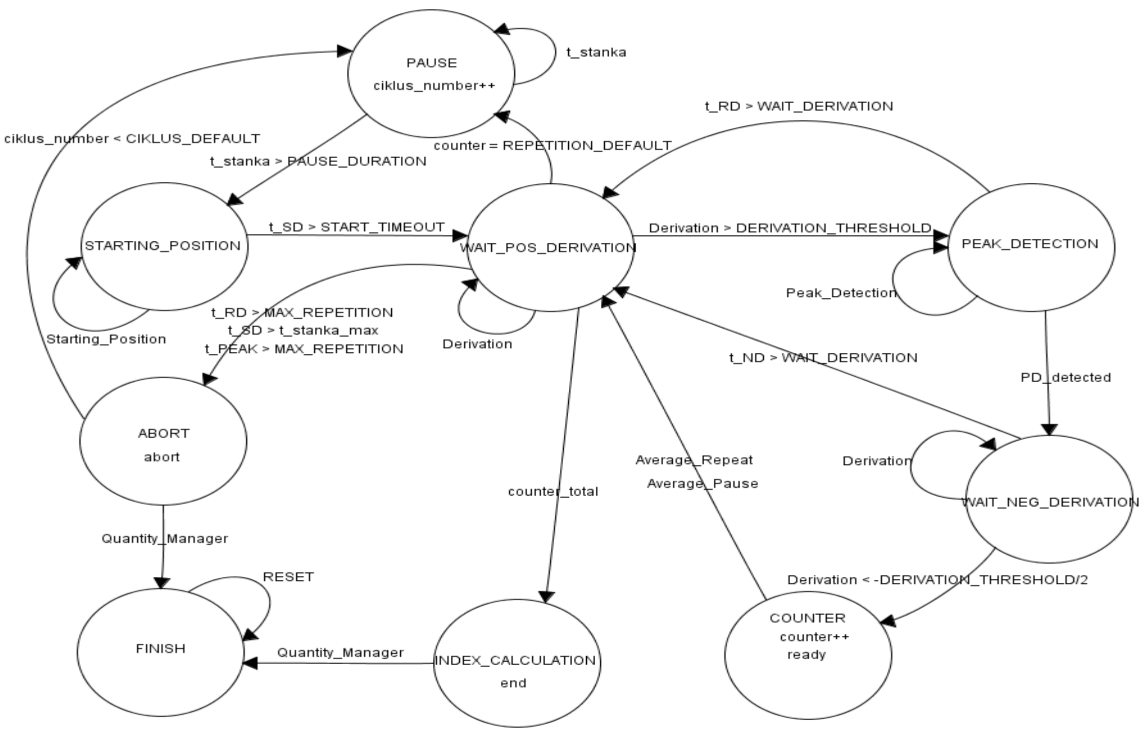

Fig. 1: Finite state machine for assisted exercising.

The FSM we implemented is shown in Fig 1. The control logic for closed loop qualitative and quantitative assessment of exercising, comprising of the FSM, Time manager block, Quality manager block and Quantity manager block is shown in Fig. 2. The input data are personalize predefined values for each exercise (mode: rehabilitation or training, threshold value, dominant axis, temporal parameters, initial conditions, number o repetitions, tolerances) and acquired signals from the sensors (i.e. accelerometer, Fig. 3.)

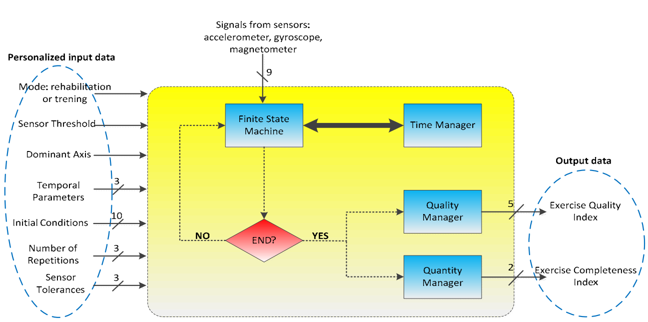

Fig. 2: Control logic for closed loop qualitative and quantitative assessment of exercising.

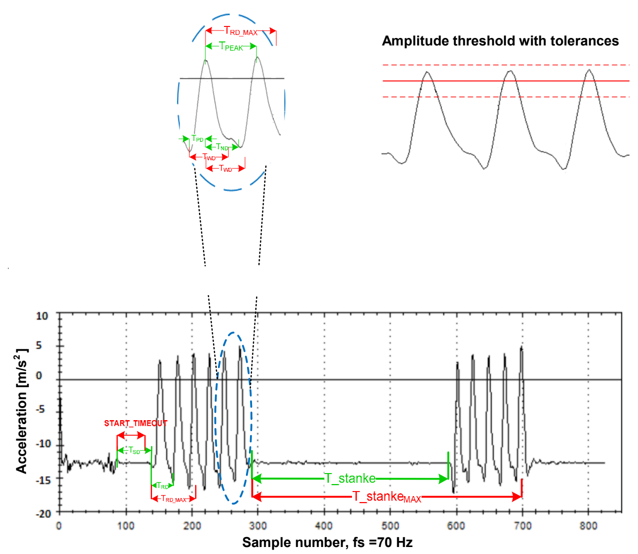

Fig. 3: Filtered acceleration signal (dominant axis) with definitions of all relevant time intervals and amplitude threshold with tolerances.

The FSM is defined by 9 states: STARTING_POSITION, WAIT_POS_DERIVATION, PEAK_DETECTION, WAIT_NEG_DERIVATION,

COUNTER, INDEX_CALCULATION, ABORT, PAUSE, FINISH and triggering condition for each transition, Fig 1. Capital letters denote constants estimated based on a number of referent measurements, while small letters denote variables that are estimated in real time for each exercise from acquired signals. Variables defined as t_{value}, where value can be SD, stanka_max, stanka_min, RD or ND denote time elapsed during or before certain action.

The FSM after an external reset (triggered by pressing RESET button on the sensor node) enters the initial state (STARTING POSITION). In this state the algorithm waits until the subject wearing the sensor node satisfies the required initial conditions of a certain exercise. Initial conditions are i.e. acceleration values (all 3 components – a_x, a_y, a_z) together with corresponding tolerances and data from other sensors (gyroscope, magnetometer), Fig. 4. This ensures proper initial position of a body part where sensor node is placed. Along with initial body position, before starting the exercise, it is necessary to satisfy the state of rest condition as well. The state of rest condition was defined as the energy of the acceleration derivative (E_{start}) which should be below prescribed START_THRESHOLD value during predefined START_TIMEOUT interval. After the initial conditions are met, the FSM enters the state WAIT_POS_DERIVATION. In this state the acceleration derivative in the dominant axis is estimated. If this value is above the predefined threshold DERIVATION_THRESHOLD, the beginning of exercise repetition is detected and the FSM enters the state PEAK_DETECTION. In this state peak of the signal is sought using predetermined threshold value based on reference measurements. Threshold value has also certain tolerances. For rehabilitation mode tolerances are larger than for training mode. These values are entered before exercise starts. If a peak is found, the FSM enters WAIT_NEG_DERIVATION state. In this state the FSM waits for the end of repetition. After the end of repetition is found the FSM enters the state COUNTER.

In WAIT_POS_DERIVATION, time between two repetitions t_{RD}, time to the first repetition in each cycle t_{SD} and time between two peaks in each cycle t_{PEAK} are measured. Depending on the measured values the FSM enters PAUSE, ABORT or INDEX_CALCULATION state. In INDEX_CALCULATION state the FSM enters when all repetitions of a certain exercise have been performed. Successful completion of the exercise is defined as a permissible deviation from the prescribed number of repetitions. In the ABORT state the FSM enters if the subject has stopped exercising. Depending on the cycle the FSM goes either to PAUSE of FINISH state.

After a subject has finished exercising Quantity manager calculates Exercise completeness index and Quality manager provides in-depth analysis of temporal and amplitude parameters of the acceleration and the initial and the end position angles. As a quality measure Exercise quality index is calculated.

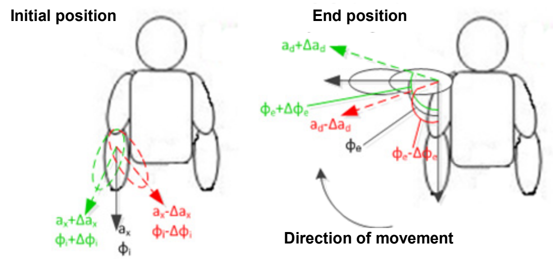

Fig. 4: Definition of the initial and the end position.

III. EXERCISE PROTOCOL FOR TESTING

All subject (7 male and 6 female students) were performing three different dumbbell exercises, Fig 5. Every exercise had three series of repetition with pause of 15 seconds after each series. In the first series the examinees had to perform six repetitions, in second they had to perform five repetitions and in the third four repetitions. The duration of each single repetition was set to 2 seconds. Exercises were performed with dumbbells having a mass of 1 kg.

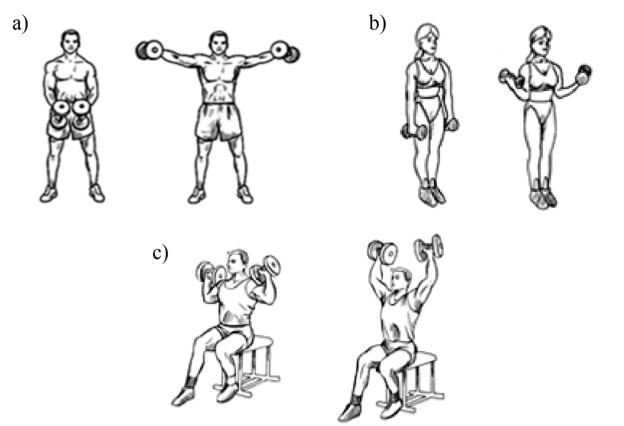

Fig. 5: Dumbbell exercises. a) Lateral raise, b) Inner-bicep curl, c) Seated shoulder press.

All subjects had auditory and visual assistance during exercising and all information about every exercise (pace, proper motion pattern) have been displayed in real-time on the screen. Signals from the sensor node were streamed to the PC where they were further processed and where feature extraction was performed so examinees had real-time estimation of motion during exercising.

IV. RESULTS

The implemented control logic performed well both in terms of quantitative and quantitative assessment of exercising. In quantitative assessment, the number of actually performed movement repetitions is counted and compared to prescribed number of repetitions. Qualitative assessment of exercising is much more complex. Feature vector comprising of 5 parameters (movement duration, local min and max acceleration on the dominant axis, average value between the initial and the end acceleration derivative, described angle) is constructed and serves as quality measure as this feature vector is compared to reference feature vector obtained by measurements on a well-trained sportsman. Here we present just a few selected parameters that contribute to the feature vector illustrating the concept of exercising quality assessment.

In Fig. 6 box plot showing distribution of movement duration during inner biceps curls exercise according to previously described protocol for all 13 examinee is presented.

In Fig. 7 box plot showing distribution of movement amplitude during seated shoulder presses is given.

In Fig. 8 a) the distribution of the initial and the end angle during lateral raises exercise is shown. For this exercise nominal initial angle is 0° and nominal end angle is 90°. In Fig. 8 b) mean absolute error of the described angle (the difference between the end and the initial angle) is shown with 90° taken as nominal reference value and with measurements from a sportsman as a reference.

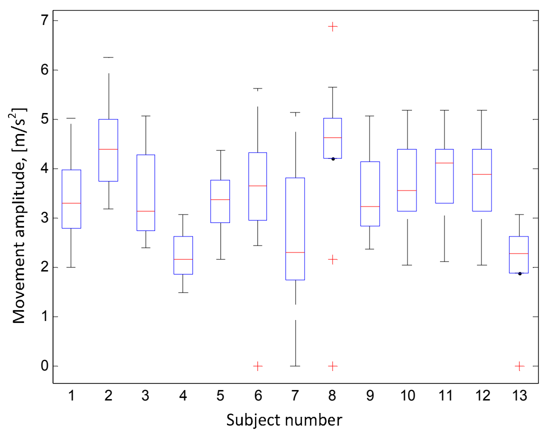

Fig. 7: Box plot showing distribution of movement amplitude during 3 series of seated shoulder presses for all 13 examinees.

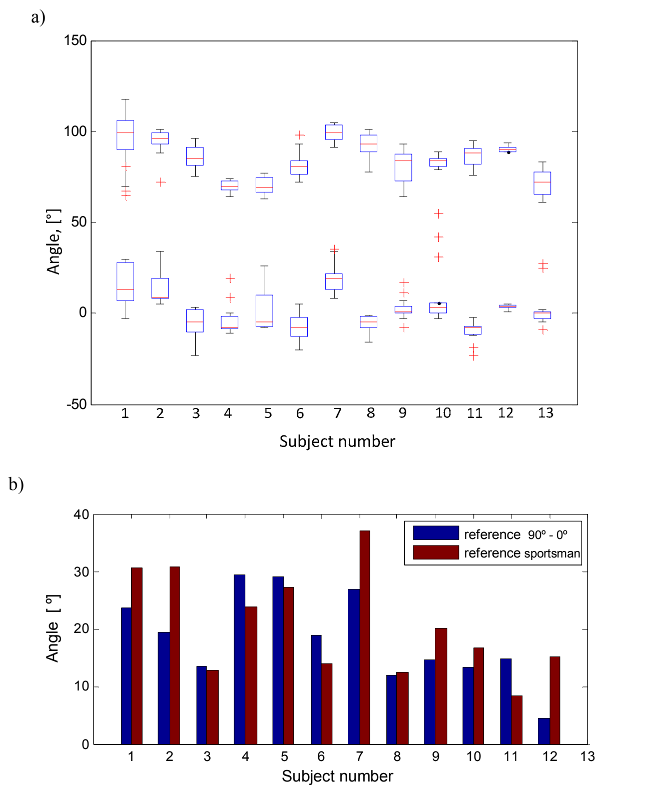

Fig. 8: a) Box plot showing distribution of the initial and the end angle during 3 series of lateral raises for all 13 examinees. b) Mean absolute error of the described angle (defined as the difference between the end and the initial angle) with 90° as a reference and with measurements from a sportsman as a reference.

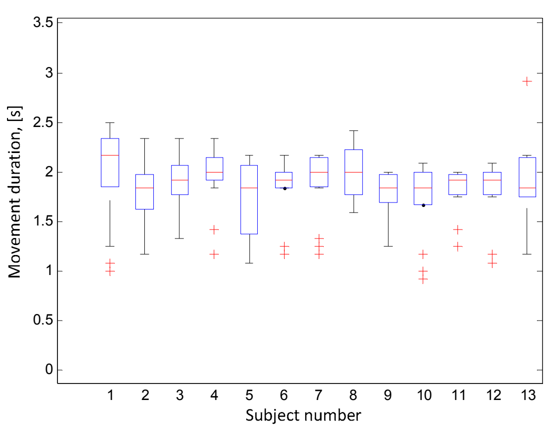

Fig. 6: Box plot showing distribution of movement duration during 3 series of inner biceps curls for all 13 examinees.

Usual definition of box plot is used: the bottom and top of the box are the first and third quartiles, the band inside the box is the median, whiskers extends to the adjacent value, which is the most extreme data value that is not an outlier, and outliers are all values larger than the third quartile plus 1.5× the interqartile range or smaller than the first quartile minus 1.5× the interqartile range (for normally distributed data this corresponding to approximately +/– 2.7σ and 99.3% coverage).

Presented results illustrate that our assisted exercising system provides, apart from closed loop control, detailed analyses of a number of parameters of performed exercises. Upon these results, thresholds, time interval duration tolerances etc. can be optimized for different exercising modes (training or rehabilitation) enabling customization and personalization according to each specific user and his rehabilitation or training plan assigned by medical specialist or trainer.

When the same exercises were performed without closed loop control (i.e. without real time audio and visual guidance) all parameters showed grater scattering comparing to closed loop condition. For example, for lateral rises, without closed loop control movement duration expressed as mean value ± standard deviation was 1.6 ± 0.9 s, and with closed loop control movement duration was 1.9 ± 0.9 s (ideally it should be 2 s). The same values for biceps curls were 1.5 ± 1.0 s, and 1.9 ± 0.2 s respectively.

V. CONCLUSION

An algorithm for assisted exercising based on Finite State Machine was developed. The algorithm can be used either for rehabilitation purposes or physical exercise training. As inputs, the algorithm uses real time signals acquired from accelerometers and gyroscopes of a sensor node in a wireless body sensor network. For testing purposes, signals were recorded from 13 healthy subjects during three different strength training exercises (lateral raise, inner-bicep curl, and seated shoulder press) while the sensor node was attached on the wrist of a subject’s dominant arm. Qualitative and quantitative assessment of the accelerometer and gyroscope signals was made. Assisted exercising with online feedback enables more precise movement control closer to prescribed pattern in time and intensity. The proposed algorithm is suitable for implementation on embedded systems. One of the potential applications of the proposed algorithm is in e-health systems such as HeartWays system [6]. HeartWays system has been designed to provide advanced solutions for supporting cardiac patients in rehabilitation providing high quality cost-effective exercise supervision at home, as in inpatient rehabilitation facilities.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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