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ORIGINAL ARTICLE

Clinical validation of a body-fixed 3D accelerometer and algorithm for activity monitoring in orthopaedic patients

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Summary *Background/Objective:* Activity is increasingly being recognized as a highly relevant parameter in all areas of healthcare for diagnosis, treatment, or outcome assessment, especially in orthopaedics where the movement apparatus is directly affected. Therefore, the aim of this study was to develop, describe, and clinically validate a generic activity-monitoring algorithm, satisfying a combination of three criteria. The algorithm must be able to identify, count, and time a large set of relevant daily activities. It must be validated for orthopaedic patients as well as healthy individuals, and the validation must be in a setting that mimics free-living conditions.

Methods: Using various technical solutions, such as a dual-axis approach, dynamic inclinometry (hip flexion), and semiautomatic calibration (gait speed), the algorithms were designed to count and time the following postures, transfers, and activities of daily living: resting/sitting, standing, walking, ascending and descending stairs, sit—stand transitions, and cycling. In addition, the number of steps per walking bout was determined. Validation was performed with healthy individuals and patients who had undergone unilateral total joint arthroplasty, representing a wide spectrum of functional capacity. Video observation was used as the gold standard to count and time activities in a validation protocol approaching free-living conditions.

Results: In total 992 and 390 events (activities or postures) were recorded in the healthy group and patient group, respectively. The mean error varied between 0% and 2.8% for the healthy group and between 0% and 7.5% for the patient group. The error expressed in percentage of time varied between 2.0% and 3.0% for both groups.

Conclusion: Activity monitoring of orthopaedic patients by counting and timing a large set of relevant daily life events is feasible in a user- and patient-friendly way and at high clinical

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validity using a generic three-dimensional accelerometer and algorithms based on empirical and physical methods. The algorithms performed well for healthy individuals as well as patients recovering after total joint replacement in a challenging validation set-up. With such a simple and transparent method real-life activity parameters can be collected in orthopaedic practice for diagnostics, treatments, outcome assessment, or biofeedback.
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Q3

Introduction

Physical activity (PA) is increasingly recognized as a major contributor to general health [1] and thus rising efforts are being made to assess activity as a quantitative parameter in the medical field [1,2]. In orthopaedics, where the movement apparatus is directly affected and treated, assessing daily life activity as an outcome dimension independent of the commonly used questionnaire-based scores for pain, satisfaction, or function is of particular interest. For assessing PA some self-report questionnaires are available
Q4 (SQUASH, LAPAQ). However, in a review of 17 of such tools, including the most popular ones, none could meet clinimetric standards and consequently the use of accelerometers was advised for monitoring [3]. Also, a recently published recommendation of the Osteoarthritis Research Society International advised sensor-based activity monitoring (AM) to assess outcomes in patients with osteoarthritis [4]._ENREF_3

Modern developments in sensor technology, such as miniaturization, have enabled the use of wearable sensor-based AM. So far, the focus of AM has mainly been on energy expenditure, which is especially popular in order to greatly limit diseases such as cardiac and pulmonary diseases; sports, lifestyle, or general health interventions are popular
Q5 to limit conditions such as obesity [5]. Many accelerometer-based AM methods only provide activity counts or caloric expenditure [6,7] based on intensity count thresholds and caloric maps, instead of identifying, counting, and timing the actual activity events such as walking. In several medical fields, however, especially in orthopaedics, one is interested in the identification of specific motor tasks and counting and timing these well-defined events instead of finding the overall intensity or caloric burn. In a recent review [8] (on AM studies under free-living conditions in orthopaedic patients) it was shown that studies which used general quantitative activity parameters such as energy expenditure, time upright, or daily steps seemed less discriminative and responsive in orthopaedic applications while more specific event counts such as minutes of moderate and vigorous PA or climbing stairs were clinimetrically more powerful.

The goal of orthopaedic interventions, besides pain relief, is the restoration of musculoskeletal function to enable the performance of activities desired by the patient or required to live independently, to participate in society, and achieve a healthy lifestyle. Thus it is highly relevant in orthopaedic outcome assessment to investigate whether, when, how often, and for how long patients are able to perform relevant and possibly challenging activities of daily living (ADL), e.g., sitting, standing, sit—stand transitions, walking, cycling, and stair climbing and descending.

As an example for choosing activity events relevant for classification in orthopaedics, ascending stairs seems very appropriate as it is the energetically more demanding task [9]. However, it is conceivable that descending stairs is motorically more difficult for patients undergoing total joint arthroplasty because of pain, loss of muscle strength, joint instability, or proprioception and a fear of falling. Thus, in patients with lower limb osteoarthritis, counting and timing of both stair events should be a highly relevant outcome measure. Cycling, stationary or on a normal bike, is a common and often recommended or prescribed physiotherapeutic activity for orthopaedic patients recovering from surgery or the elderly osteoarthritic patient in general [10]. Cycling is also an important activity for social participation for many, so that its classification adds great value to outcome assessment or supervising the compliance to therapy. Step counters and most commercial monitors cannot distinguish between walking and cycling.

Several AM devices with analysis software such as Actigraph (Pensacola, FL, USA), StepWatch (Washington, DC, Q6
USA), Shimmer (Dublin, Ireland), Dynaport (Den Haag, The Netherlands), ActivPal (Glasgow, UK), Gaitup (Renens, Switzerland), RT3 and others have already been developed and are commercially available [7,8,11—17]. However, their algorithms are usually proprietary and nondisclosed, they do not identify all of the aforementioned activities, or are not always patient and user friendly (e.g., bulky). Furthermore, to date only a few studies have validated their algorithms on patients whose movement apparatus has been affected [18—20]. In these patients there is a broad range of activity levels, ranging from being able to walk only very short bouts with the help of walking aids (1st week postoperatively), to uninhibited movement at the level of a healthy individual. Not only does a patient's condition influence his or her activity level, but also the way a movement is performed (i.e., slower, lower intensity, use of walking aids) challenges the universal validity of signal analysis algorithms. Thus, this could affect the performance of AM devices when used to monitor orthopaedic patients [21—23]. Therefore, it is important to validate AM algorithms using individuals representing the intended target group.

Due to miniaturization of sensors and chips, it has become feasible to increase the data-storage capacity of devices, enabling 100% postprocessing of data. This in turn enables the creation of AM algorithms that are hardware

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