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Preliminary evaluation of reliability and criterion validity of Actiwatch-Score

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Abstract—The restoration of normal physical activity is a primary objective of most chronic pain rehabilitative interventions, yet few clinically practical objective measures of activation exist. Actigraphy is one technology that promises to fill this void in the field of pain outcomes assessment. This study evaluates the measurement properties of one of several commercially available actigraphs: the Actiwatch-Score (AW-S). We conducted separate trials to examine concordance between units when worn concurrently at the same and different body sites and to compare the AW-S to a validated optical three-dimensional motion-tracking system. The data indicate that the AW-S has excellent interunit reliability and good criterion validity, but its intersite reliability varies with activity type. These results suggest that this device, and those like it, warrants further investigation and is likely to yield valuable data regarding the optimal application of this technology.

Key words: accelerometry, actigraphy, Actiwatch, criterion validity, optical motion-tracking, pain, rehabilitation, reliability, treatment outcomes, VICON.

INTRODUCTION

The restoration of normal physical activity is a primary objective of most chronic pain rehabilitative interventions [1]. Often termed "functional restoration," the biopsychosocial approach to pain treatment typically includes graded exposure or progressively increasing goals for the general physical activity level as well as for strength, range of motion, and endurance exercises despite the patient's pain [2]. This approach targets insidious restrictions in the intensity, duration, and range of physical activities that often characterize the behavioral patterns of individuals with moderate-to-severe chronic pain syndromes. Strong evidence has shown that intensive multidisciplinary treatment programs that include a functional restoration component are more effective than interventions that do not [3]. Reflecting this emphasis, current standards for performance monitoring include functional activation among the key indices of treatment effectiveness [4].

Although several validated self-report measures of pain interference in physical activities are available (e.g., Pain Outcomes Questionnaire [5], West Haven-Yale Multidimensional Pain Inventory [6]), the accurate assessment of changes in activity levels following pain intervention

Abbreviations: 3-D = three-dimensional, AW-S = Actiwatch-Score, R&D = research and development, SCI = spinal cord injury, SD = standard deviation, VA = Department of Veterans Affairs.

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remains a challenge. Investigations of the accuracy of self-reported functional capacities among individuals with chronic pain indicate that patient assessment often differs significantly from objective measures of actual capacities [7–8], particularly if long-term recall is required [9]. Although several self-report measures have been developed to assess physical activity levels in chronic disease populations, the validity of this approach is limited by patient motivation, memory errors, and other response biases. Perhaps the most problematic response bias known to affect these self-report instruments is the patient's tendency to recall and report only the more salient aspects of physical activities over longer time periods. As a consequence, most self-report measures do not adequately capture the changes in habitual activity patterns that are expected outcomes of pain intervention [10]. A reliable and valid objective measure of physical activity would improve identification of pain-related inactivity and risk for deconditioning, promote greater consistency in measurement across treatment sites, and facilitate outcomes comparisons across treatment approaches and programs [11].

One technology that promises to fill this void in pain outcomes assessment is a form of user-worn accelerometry called "actigraphy." Well validated as a low-cost alternative technology for assessing sleep disorders [12–15], actigraphy has more recently been recognized as a potential objective measure of change in physical activity among pain patients [16–17]. Since the small body-mounted devices can capture and store moment-by-moment activity data for an extended time period while patients are living in their natural environments, actigraphy facilitates sampling of a more representative pattern of activity than may be seen in clinical settings. In addition, it is not subject to the biases and unreliability that characterize observer ratings and self-ratings. Although early models were quite expensive to acquire and maintain, the cost of several commercially available actigraphs is now within reach for clinicians as well as researchers.

Good general empirical support exists for the validity of actigraphy as a measure of physical exertion in healthy populations under laboratory and, to a lesser extent, in free-living conditions [18–19]. However, large differences in validity coefficients and optimal calibration formulas are commonly found across actigraph types, target populations, and body placement sites [18,20–21]. These findings have prompted experts to recommend that all actigraph configurations be validated in the specific populations and settings in which they will be applied. Testing protocols that incorporate free-living behavior samples or laboratory tasks that approximate the type and intensity of activities normally performed by the target group are preferred [10,22].

Few published reports have examined the validity of actigraphy for measuring general physical activity in populations likely to demonstrate altered patterns of activity, such as individuals with chronic pain. However, the limited available data do suggest that accelerometry may be valid for a wide range of applications in pain populations. In an early application of accelerometry, failed back surgery patients wore four body-mounted units (one on each upper leg, two on the trunk) while performing a number of household functional activities. Comparison with visual analysis of simultaneous video recordings indicated a high degree of agreement (87%) between the two methods of activity quantification, suggesting that the four-unit accelerometer system was a valid measure of pain-relevant behaviors such as duration of activities and number of transitions [23]. Korszun et al. found that patients with both fibromyalgia and depression exhibited lower daytime activity counts than nondisabled controls [24]. Among individuals with chronic low back pain who were asked to perform their normal daily activities over a 14-day period, accelerometer data predicted (r = 0.72) energy expenditure measurements obtained with the criterion standard doubly labeled water technique [25]. Schasfoort et al. reported that individuals with nonacute upper-limb Complex Regional Pain Syndrome Type I produced lower intensities and percentages of activity with the affected limb than with the unaffected one [26]. The Actiwatch-Score (AW-S) (Respironics/Mini Mitter Co, Bend, Oregon), the subject of the current study, has been found to discriminate the peak and high-level activity of individuals with fibromyalgia from that of matched controls [27]. Finally, in a time-series analysis of the relationship between activity and pain over a 3-week period, acute back pain patients demonstrated significant cross-correlation (r = 0.22–0.48) between accelerometer data and pain intensity ratings recorded in an electronic diary. As these patients improved, the cross-correlation between activity and pain disappeared. A comparison group of patients with chronic pain did not demonstrate a significant relationship between pain and activity [17].

While encouraging, these data provide only preliminary support for the use of actigraphy in pain populations.

Systematic evaluations of the measurement properties of specific accelerometer technologies in diverse pain populations are still needed. At present, no single commercially available device has been scientifically scrutinized to this level in pain populations, and the field has only begun to explore the possibilities for analysis and application of accelerometer data of any type. In addition, consensus has not yet been reached about which body site should be used to measure whole-body activity. The current study is the first step in a systematic effort to validate one commercially available actigraph for use as a measure of pain treatment outcomes. The AW-S uses an omnidirectional accelerometer to record the occurrence and degree of acceleration associated with motion. This information is stored in onboard memory as activity counts that can be downloaded and summed to form a measure of general physical activity. Unlike some commercially available devices, the AW-S is sensitive to acceleration in all three dimensions, which is an accelerometer design feature that has been found to be more accurate than the more common unidimensional technologies [17,28]. This study is the first phase of a multiphase evaluation of the validity and clinical utility of the AW-S in pain populations. This phase of the project evaluates interunit and intersite reliability and compares the AW-S system of quantification of human movement with that of a validated optical three-dimensional (3-D) motion-tracking system, the VICON Motion Analysis System (VICON, Oxford Metrics Group; Oxford, United Kingdom), in a small convenience sample of individuals who do not experience significant chronic pain. Although this study did not employ a chronic pain sample, the results lay the foundation for a systematic program of research evaluating the measurement properties of the AW-S in chronic pain inpatient, outpatient, and spinal cord injury (SCI) populations.

METHODS

Instruments

Actiwatch-Score

The AW-S uses an accelerometer built from a cantilevered rectangular piezoelectric bimorph plate and seismic mass that is sensitive to movement in all directions. This type of sensor integrates the degree and speed of motion and produces an electrical current that varies in magnitude. Increases in the degree and speed of motion produce an increase in voltage, and this information is stored as an activity count. The maximum sampling frequency is 32 Hz. The device weighs 21 g and measures 31 × 28 × 10 mm. The devices were programmed to store data in 15-second epochs for maximum sensitivity.

VICON Motion Analysis System

The VICON Motion Analysis System (VICON, Oxford Metrics Group; Oxford, United Kingdom) is a commercially available technology that uses optical-reflective markers to measure 3-D movement. The VICON is a standard technology in many medical and biomechanical industries for capturing and modeling human motion [29]. The data provided by the system can be used to derive a measure of acceleration for specific body sites that can serve as a criterion standard for accelerometer data. Optical-reflective markers are placed on body sites of interest, and a matrix of 12 wall-mounted cameras track marker positions in 3-D space. The independently documented linear and angular accuracies of the VICON technology are 0.1 mm and 0.15°, respectively, with no recorded drift [30]. Program outputs for this study were computed at the data collection frequency of 60 Hz.

Procedures

This study consisted of two procedures, interunit and intersite reliability and criterion validity, that were conducted separately. The local research and development (R&D) committee approved all procedures.

Interunit and Intersite Reliability

A 2-hour trial was designed to test the concordance between AW-S units when worn at the same body site (interunit reliability) as well as that between units worn at different body sites (intersite reliability). For each subject, two units were securely strapped together and attached to the body as a single piece at each potential site: superior to the radiocarpal joint (wrist), the iliac crest (waist), and superior to the lateral malleolus (ankle). Based on manufacturer instruction, we placed the units on the nondominant side of each subject. From a pool of 20 units, 6 units were randomly chosen for testing. Unit placement was rotated across the three subjects (two male investigators and one female investigator) so that no unit was tested at the same site twice and no pair was matched more than once. The subjects were instructed to perform their normal daily activities during testing. For Subjects 1 (male, 39 years old, 6 ft 2 in. tall, 227 lb) and

2 (male, 54 years old, 5 ft 10 in. tall, 188 lb), the trial was conducted during the performance of normal household chores and activities (e.g., cleaning, sweeping, reading, working at the computer). For Subject 3 (female, 55 years old, 5 ft 8 in. tall, 187 lb), the trial was conducted during the performance of routine clinical-care activities in an outpatient setting (e.g., reviewing charts, examining patients, walking between the examination room and the front desk). Sleep was not assessed in this study because the validity of the device for this purpose has been well established [14–15]. None of the subjects had any significant disability. The 2-hour trial provided 480 data points for each unit.

Criterion Validity

We examined the ability of the AW-S to measure 3-D human movement using the VICON System. To provide the most realistic model of physical activity possible, we evaluated the AW-S during a single subject's (Subject 1 from the reliability procedure) performance of two 15-minute trials of exercise activity commonly prescribed for back pain rehabilitation. The first trial consisted of the performance of standard physical therapy exercises for lumbar stabilization including pelvic tilts, bridges, leg lifts, prone extensions, and lunges. The second 15-minute trial consisted of walking at a pace of approximately 1 m/s. We selected this procedure to ensure that the range of acceleration was within normal human limits and represented that which is observed during the types of physical activity promoted by standard pain rehabilitation interventions. Three randomly selected AW-S units were attached to the wrist, waist, and ankle of the subject's nondominant side. A primary VICON optical-reflective marker was attached directly to each AW-S, and secondary markers were placed in a triangular pattern around each device. The use of secondary markers allows one to estimate the position of the primary marker should it become momentarily hidden from the 12-camera system by the subject's body or other unexpected obstructions. This is a standard and reliable method for handling missing data points due to primary marker occlusions. Each 15-minute trial provided 60 data points for each AW-S and 648,000 (54,000 per camera) for each VICON marker.

Data Analysis

Interunit and Intersite Reliability

AW-S data were downloaded from the units and then exported from Actiware Version 5.0 software [31] into a comma-delimited text file that was cleaned of extraneous data and imported into an SPSS 12.0 data file [32]. We transformed the AW-S data using a centered moving average function with a span of two. Pearson's correlation coefficients (r) were computed for all interunit and intersite combinations of watches used in the trial. Correlations between matched pairs at a single body site (i.e., between the two units at a given body site) represent an index of interunit reliability, and associations among units located at different body sites provide an index of the degree of concordance between placement sites (which is being conceptualized as intersite reliability). Correlation coefficients, which were computed separately for each subject (n = 3), were averaged across subjects within each possible body-site combination. This procedure provided a single mean correlation coefficient for each of the 15 possible combinations (3 interunit and 12 intersite) of the 6 placement sites (2 each at the wrist, waist, and ankle).

Criterion Validity

Missing VICON data points due to an occlusion of the primary marker during the two trials were computed using positional information supplied by the secondary markers. Fast Fourier transform analysis of the independent series of data were performed with MATLAB software for identification and filtering of any sources of noise inherent in the data signals [33], such as electrical noise and fluorescent lighting. The VICON data were resampled at 32 Hz to match the sampling rate of the AW-S. Visual Basic (version 9.0, Microsoft Corporation, Redman, Virginia) macros were written for computing the second derivative measure of motion, acceleration (millimeter per square second), from the VICON data, and peak acceleration values for each 1-second period were recorded. Peak acceleration scores were summed over each 15-second interval for the provision of a criterion measure for comparison with the corresponding AW-S 15-second epoch activity count for both trials. AW-S and VICON data were transformed with the use of a centered moving average function with a span of two. The validity of the AW-S technology was evaluated through calculation of the strength of association between the bench-validated filtered derivative VICON measure of acceleration and the AW-S activity counts for the three placement sites in each of the two trials. Correlation coefficients were computed for all combinations of measures.

RESULTS

Interunit and Intersite Reliability

Mean activity counts ± standard deviation (SD) for the wrist, waist, and ankle placements ranged from 54.8 ± 67.1 to 115.4 ± 105.3, 22.3 ± 47.4 to 69.4 ± 111.0, and 53.8 ± 105.7 and 205.5 ± 211.4, respectively. Mean correlation coefficients are presented in **Table 1**. The mean interunit coefficients revealed excellent agreement between matched units within each placement site. Mean intersite coefficients indicated that waist and ankle activity measurements were highly correlated ($\bar{r}$ = 0.97 ± 0.01). However, wrist measurements demonstrated more modest agreement with the waist ($\bar{r}$ = 0.56 ± 0.03) and ankle ($\bar{r}$ = 0.58 ± 0.06) measurements.

Criterion Validity

Mean activity counts for the wrist, waist, and ankle placements were 70.4 ± 54.9, 17.0 ± 20.1, and 105.5 ± 77.8 for Trial 1 and 69.0 ± 56.2, 66.0 ± 36.1, and 463.4 ± 240.2 for Trial 2, respectively. The results of the criterion correlational analyses are presented in **Table 2**. In the lumbar exercise trial, AW-S wrist and waist placement activity counts were highly correlated with the corresponding VICON criterion measures of acceleration, while the AW-S ankle placement was moderately correlated with the VICON criterion measure. AW-S waist and ankle measurements were moderately correlated with each other, and the strength of association was similar to that observed between VICON measurements at those body sites. In the walking trial, AW-S waist and ankle placement activity counts demonstrated excellent associations with the corresponding VICON criterion measures of acceleration, while the AW-S wrist placement was more moderately correlated with the VICON wrist measure. During the walking trial, AW-S waist and ankle measurements were highly correlated with each other, and as observed during the lumbar exercise trial, the strength of association was similar to that observed between the corresponding VICON measurements. Both AW-S and VICON wrist measurements demonstrated weak-to-moderate correlations with ankle and waist measurements across the lumbar and walking trials.

DISCUSSION

The results of this preliminary investigation indicate that the AW-S has excellent interunit reliability and good criterion validity when used at any of the three potential

Table 1.
Actiwatch-Score mean interunit and intersite reliability correlation coefficients (Pearson's *r*).

Measure	1	2	3	4	5	6
1. Wrist 1	—	**0.98**	0.54	0.59	0.56	0.55
2. Wrist 2	—	—	0.53	0.58	0.66	0.54
3. Waist 1	—	—	—	**0.99**	0.98	0.98
4. Waist 2	—	—	—	—	0.96	0.97
5. Ankle 1	—	—	—	—	—	**0.99**
6. Ankle 2	—	—	—	—	—	—

Note: Bold-faced values represent Actiwatch-Score interunit reliability coefficients.

Table 2.
Intercorrelations among Actiwatch-Score (AW-S) and VICON Motion Analysis System (Oxford Metrics Group, Oxford, United Kingdom) measures.

Measure	1	2	3	4	5	6
1. AW-S Wrist	—	0.48	–0.11	**0.88**	0.34	0.11
2. AW-S Waist	0.05	—	0.32	0.49	**0.88**	0.48
3. AW-S Ankle	0.01	0.93	—	–0.25	0.37	**0.72**
4. VICON Wrist	**0.67**	0.52	0.52	—	0.51	0.21
5. VICON Waist	0.06	**0.95**	0.88	0.54	—	0.65
6. VICON Ankle	0.13	0.93	**0.97**	0.60	0.89	—

Note: Lumbar exercises are given above diagonal and walking below diagonal. Bold-faced values represent AW-S criterion validity coefficients. Critical values (two-tailed test) for *r* were 0.28 for $\alpha = 0.05$ and 0.36 for $\alpha = 0.01$.

placement sites. However, examination of the pattern of criterion validity coefficients across the lumbar exercise and walking trials suggests that each placement site is subject to activity-dependent limitations in the accuracy of measurement. Ankle and waist placement provided much better measurement of walking activity, while wrist and waist placement was the best measurement of the mostly supine lumbar exercises. Interestingly, VICON and AW-S wrist measurements of lumbar exercise activity were moderately correlated with the waist measurements of both technologies, but the relationships with ankle measurements were generally poor. This pattern of associations was not found for walking activity because the VICON wrist measurements were moderately correlated with all other measurements, but AW-S wrist measurements were not. The reason for this discrepancy is unknown, and this finding warrants further investigation.

Given the high degree of reliability of the AW-S and its ability to demonstrate very strong relationships with an external measure of acceleration (e.g., AW-S ankle correlation with VICON ankle during walking, $r = 0.97$), the pattern of variation in criterion validity coefficients suggests that the recommended placement of any accelerometer-based technology should be determined based on the target activity of clinical or scientific interest. Strong empirical evidence supports the use of wrist placement for sleep assessment [12–13], but the current study suggests that waist or ankle placement may be more appropriate for general activity, particularly if ambulation or other weight-bearing activity is an important component of the target behaviors. These findings are consistent with other studies indicating that accelerometer-based measurement of upper-limb activity adds little to the prediction of energy expenditure after waist measurement is considered [34]. In the case of pain treatment outcomes assessment, ankle or waist placement may provide a better measure of overall energy expenditure and, therefore, a superior index of the types of changes in functional activation that are the focus of chronic pain rehabilitation. However, additional work is needed to determine whether these associations are similar among individuals who exhibit lower levels of activation or who have significant impairment that prevents normal ambulation.

The current study has some methodological limitations that should be noted. The assessment of activity during the two procedures of this study was conducted over relatively brief time periods with only a minimal number of subjects who were not chronic pain patients, and as a result, the range of behaviors assessed may not represent the full range or intensity of those likely to be observed in clinical populations. Although it is not likely that interunit reliability estimates would vary significantly under different experimental conditions or when the AW-S is worn by different individuals, it appears that criterion validity is dependent on the range and type of activities to be measured. In addition, although the VICON System accurately quantifies human motion through 3-D space, it does not estimate energy expenditure associated with that movement. Future studies should address these issues by comparing actigraphy with measures of energy expenditure (e.g., oxygen-uptake analysis) during the performance of a broader range of behaviors among subjects with physical impairments and pain-related disability. Evaluation of the relationships between activity counts from different body sites and measures of energy expenditure across activity types and intensities will allow stronger and more specific recommendations regarding optimal actigraph placement for clinical and research applications. In addition, the examination of diverse clinical samples will allow the calibration of formulas that can be used to estimate energy expenditure for specific applications and populations. Finally, if the AW-S is ultimately to be used as a measure of pain treatment outcomes, its sensitivity to treatment-related changes in functional activation among individuals with pain-related disability will be crucial to demonstrate. Phases 2 and 3 of this project, which are currently underway, are designed to answer these questions using samples of chronic pain patients with and without SCI. It is hoped that this multiphase project will demonstrate the scientific merit of the use of one actigraph, the AW-S, as a measure of pain treatment outcomes.

CONCLUSIONS

The results of this study support the potential value of actigraphy in general and the AW-S in particular as a measure of pain treatment outcomes. While these data do not provide sufficient validation of the AW-S for this application, they do suggest that further investigation of the validity and clinical utility of this device, and others like it, is warranted and likely to yield valuable information regarding the optimal application of this technology in pain populations.

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