Feasibility of a Low-cost Microcontroller Based Lumbar Flexion-relaxation Phenomenon Monitoring System

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ABSTRACT

This paper investigates the potential of using a low-cost microcontroller based system to monitor the lumbar flexion-relaxation phenomenon in the erector spinae muscle. A BITalino microcontroller was interfaced with an electromyography sensor and accelerometers. The data was combined in Matlab. The results indicate that the system is capable of visually demonstrating the presence of the lumbar flexion-relaxation phenomenon.

INTRODUCTION

More than half a century ago, Floyd and Silver [1] described the lumbar flexion-relaxation phenomenon (FRP) as a myoelectric silence of the m. erector spinae in a fully flexed trunk posture. Several authors have studied this phenomenon since then focusing on the effects of gravity [2] and flexibility [3] or FRP’s potential applications in worker training [4] or rehabilitation [5].

Holleran et al. [4] proposed, that FRP could be used in a feedback device to signal trunk flexion angles where the non-muscular parts of the spine are at risk for injury. This requires simultaneous detection of electromyography (EMG) and trunk flexion angle, intervention criteria, and an actuator to provide visual or auditory feedback. Traditionally electromyography has been expensive to utilize, however, the recent trend towards the do-it-yourself mindset has made EMG acquisition available with low-cost and considerable quality [6], [7]. These low-cost EMG acquisition solutions can be easily interfaced with other types of sensors, like accelerometers, which for a while have been used for inclinometry [8], [9], [10].

This paper investigates the potential of using a low-cost microcontroller based system for FRP monitoring. The paper focuses on three aspects. First, is the resolution of a contemporary low-cost microcontroller sufficient to distinguish periods of low myoelectric activities? Second, is the resolution of a contemporary low-cost

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microcontroller sufficient to provide accurate inclinometry measurements in the whole range of movements? Third, is the sample solution overall capable of producing the desired result? As a feasible solution would be a valuable tool for educators and safety specialist to demonstrate the ergonomic principles during lifting.

INCLINOMETRY

It is possible to specify the orientation of a triaxial accelerometer in a two-dimensional space, as the deviation from gravitational acceleration may be described by its perpendicular components. It is evident from figure 1 that in the case of simplistic movements, such as trunk flexion or extension, two of the three axes can be used to describe the inclination by their deviation from the gravitational acceleration. However, another question is whether both of the accelerometer’s axes are needed, as the output of each analog sensor axis occupies a channel in the microcontroller. There are two major issues that need to be considered in order to make the decision. First, the body segment’s range of motion (ROM) should be considered. Both the sine and cosine functions have unique values only in half of the 360° range (figure 2), thus measuring ROM > 180° requires the two axes and ROMs < 90° can be measured with one axis. Second, the inverse sine and cosine functions are quite linear in the mid-range of the functions (figure 3). Meanwhile, at the functions’ extremes the relationship is curved and acquiring the values may challenge the 10-bit microcontroller’s resolution (figures 4-5). Figures 4 and 5 demonstrate the fact that if the alignment is expressed as a sine or cosine function, then the calibration process requires only two points [11] to reach a level of accuracy comparable to the multi-point calibration procedure. Evidently the result of a sine or cosine transformation is a linear relationship between the alignment and accelerometer output, thus using multiple points on figure 5 is redundant.

![Figure 1. Alignment of the accelerometer’s axes.](image1)

![Figure 2. Values of sine and cosine functions in full rotation.](image2)

![Figure 3. Values of reversed sine and cosine functions.](image3)
MATERIALS AND METHODS

Equipment

A BITalino telemetric microcontroller with the OpenSignals (r)evolution software (both PLUX wireless biosignals S.A., Portugal) was used for data acquisition and visualization. The microcontroller’s operating voltage is 3.3 V, and the analog signal is converted to digital with a 10-bit A/D converter (typical resolution of low-cost microcontrollers), meaning the resolution of an analog channel is 3.2 mV. With this resolution and sample rate of 1000 Hz, the microcontroller is capable of wirelessly transmitting the data of four channels. One of the channels was reserved for an EMG sensor v.151015 (PLUX wireless biosignals S.A., Portugal), the remaining three channels were interfaced with ±3g range tri-axial accelerometers ADXL335 (Itead Intelligent Systems Co ltd, China).

Deployment and Procedure

Several variants of the body segment’s alignment were identified in an unrestricted flexion maneuver (figure 6). The thigh segment may be deviated a few degrees to either side of the g-axis. Describing such an alignment requires one accelerometer’s axis and a sine function. Considering the trunk extension and flexion ranges it is evident, that data from two axes is required to describe the trunk angle. A multi-valued inverse tangent function—atan2—(figure 7) was found to be a suitable solution to obtain the trunk angle values as the function has unique values in the whole 360° range. A custom Matlab (MathWorks, Inc., Natic, USA) script was used to calculate the angle between the trunk and the thigh. A Butterworth second order low pass filter with the cut-off frequency set to 8 Hz was used to smooth the accelerometer data. The trunk-thigh angle (TTA) was defined by equation 1, trunk angle (ACC1) by equation 2 and thigh angle (ACC2) by equation 3. ADCi refers to the microcontroller’s reading of accelerometer ‘i’, while ‘a’ and ‘b’ refer to the slope and intercept of the calibration.
TTA = 180 – ACC1 + ACC2  \hspace{1cm} (1)

ACC1 = 90 + \text{atan2}(-\text{ADC1}_x \times a_x + b_x, \text{ADC1}_z \times a_z + b_z) \times 180 \times \pi^{-1}  \hspace{1cm} (2)

ACC2 = \text{arcsin}(\text{ADC2} \times a + b)  \hspace{1cm} (3)

For ACC1 the accelerometer was strapped to the subject’s back about the level of T9. The ACC2 accelerometer was strapped to the subject’s thigh roughly about two thirds of the distance from the knee to the hip socket.

The subject was instructed to carry out the flexion maneuver smoothly and hold freely chosen angles for a few seconds. In addition, to avoid sudden changes in back loading and corresponding changes in the EMG, the subject held their hands close to the body and maintained a neutral neck posture. Kinovea (v. 0.8.15) software was used to obtain visually perceived TTA. In the second test the accuracy was measured on a simple test rig (Figure 8).

Figure 6. Variants of segmental alignment; • – accelerometer, Ax – accelerometers x-axis; Az – accelerometers z-axis; θ – angle between gravity and accelerometer axes.

Figure 7. Values of arctan and atan2 functions.

Figure 8. Test-rig for accuracy assessment.
RESULTS AND DISCUSSION

The absolute difference between the visually perceived angle and the accelerometer based measurement was statistically significantly \[ t(29) = 2.934, \quad p = 0.007 \] greater when the accelerometers were attached to the subject \( (M = 6.8, \quad SD = 4.9) \) than in the case when the accelerometers were mounted on the test rig \( (M = 2.8, \quad SD = 1.7) \). This is an expected result for several reasons. First, both the visual and accelerometer based systems have systematic errors. The visual system relies on the accurate placement of markers and is also susceptible to visual parallax either by the viewing angle or camera location. Meanwhile, the accuracy of the accelerometer based system depends on the calibration procedure and the precision may be affected by the location of the accelerometer attachment. As the spine is curved by its nature, the spinal regions have different trajectories during the trunk flexion. Thus the high agreement between the perceived and measured angles requires also agreement between the accelerometer’s location and visual cues. Identification of such locations was not the main objective of this study. However, a high correlation between visual and accelerometer based results is evident from Figures 9 and 10. This allows concluding that the abovementioned statistically significant difference is to a large extent a matter of sensor attachment.

The comparison between the raw EMG and TTA show a myoelectric response to spontaneous swaying movements during standing upright. Furthermore, Figure 11 clearly indicates the presence of FRP during the subject’s full flexion, which is in agreement with the study of Floyd and Silver [1].

Although the FRP is may be visually detected by human eye, there are limitations when setting criteria for automatic FRP detection. After rectifying and smoothing the raw EMG data with a Butterworth second order low pass filter \( (f_c = 2 \text{ Hz}) \) the FRP region had EMG value from 1-3 ADC units. Meanwhile, the postures between standing upright and full flexion output values 10-20 ADC units. This is a relatively small change considering that the full range is 1023 ADC units. For automatic FRP detection either a microcontroller with a higher ADC resolution or an EMG amplification circuit with a higher gain factor is needed.

![Figure 9. Comparison of the accelerometers’ output angles and angles on the test rig.](image1.png)
![Figure 10. Comparison of the trunk-thigh angles measured with accelerometers and Kinovea.](image2.png)
Overall, the sample solution tested in the study succeeded to provide the desired result in the laboratory settings. Therefore, the sample solution has potential to be used in a laboratory or an educational setting where simulated work can be studied or its effects demonstrated. However, in the current stage the sample solution cannot be applied in real world settings as it is. Further research is required to develop the means for feedback. In this study the data was processed externally in Matlab, which allowed for visualization in a personal computer. In real word, the data should be processed on the device or on a smartphone. The latter may also be used for user interface or feedback.

CONCLUSIONS

The results suggest that the low-cost system tested in the study is sufficient for accurate inclinometry and visually detecting the lumbar flexion-relaxation phenomenon. The use of the tested system to provide flexion-relaxation phenomenon feedback is to some degree restricted by the resolution of the 10-bit microcontroller and the gain factor of the EMG amplifier.

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