Application of the Teagar-Kaiser energy operator and wavelet transform for detection of finger tapping contact and release times using accelerometer

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Abstract

The Teager-Kaiser energy operator (TKEO), when applied to a signal gives an estimation of the instantaneous energy of that signal. It, therefore, accentuates both frequency and amplitude changes in a signal. To date, it has been primarily used in communications systems and most popularly in electromyographic signal analysis to detect bursts of muscle activity, however, it has the potential to be used in a number of applications including accelerometer and movement data.

A new algorithm was developed which used the TKEO to detect contact times during a finger tapping task from accelerometer data recorded from the index finger. The accuracy of the algorithm was assessed in 7 healthy control subjects during continuous finger tapping across a range of frequencies from 0.5Hz to 2.5Hz. The algorithm proved to be sensitive, correctly identifying at least 99% of all contacts in each of the finger tapping conditions that were tested. The mean absolute error of the contact detection is 14.7 ± 6 ms, while the mean absolute error of the release detection is 36.5 ± 36.3 ms. The proposed algorithm provides a method for the automatic detection of the temporal occurrences of the events of the finger tapping task using only a tri-axial accelerometer. The approach presented provides a means for objective assessment of finger tapping tasks for evaluation of the fine dexterity of the upper limb

Introduction

Finger tapping is one of the tasks used in assessing motor function in a number of movement disorders including Parkinsons Disease and Huntingtons Disease [1]. At present, this task is assessed subjectively by a clinician to determine how the current disease state is affecting the fine motor skills of the respective patient. Due to the subjective nature of the movement disorders rating examinations, there is a potential for inter-rater variability in outcome ratings of the exam [2]. Hence, there is a current need for a low cost, objective measure to assess the function of the participants during the various tasks of the movement disorders rating scale examinations.

Tri-axial accelerometers provide a low-cost, lightweight and portable solution to accurately measure the complex movements of a body. They are increasingly popular in studies of human movement analysis to study gait and other clinical tasks [3], [4].

A number of different sensor types have been used to assess the finger tapping task such as gyroscopes, hall-effects magnetic sensors, touch sensors and accelerometers [5]–[7]. These studies use characteristics of the recorded signals to infer features of the finger tapping task such as the temporal occurrences of contact and release of the index finger and the thumb as well as quality of the movement during the task. None of these studies, however, validated the detection of these features using robust ground truth data.

The Teager-Kaiser energy operator estimates the energy of a signal which is derived from the instantaneous amplitude and instantaneous frequency of the signal. Thus, it can be used to detect instantaneous changes in either amplitude or frequency in a given signal. Due to its abilities to enhance high amplitude and frequency changes in signals, the TKEO has been used to detect the onset of muscle activity in the electromyogram signal during various movement tasks [8], [9], to image contrast enhancement [10]. In this paper, we introduce a novel algorithm that uses the TKEO in conjunction with a variant of the discrete wavelet transform, the Maximal Overlap Discrete Wavelet Transform (MODWT), to find the temporal occurrences of the index finger and thumb contacts and releases during finger tapping. The performance of the proposed algorithm is assessed in healthy control subjects where contact times are recorded using touch sensors located on the contact surfaces of the index finger and thumb respectively.

Methods and Materials

A. Participants

7 healthy, young participants (2 female, age: 24.57 ± 1.51) gave their informed consent to participate in the study. Research ethics approval was obtained from the board of Research Ethics, University College Dublin before the commencement of the study.

B. Experimental Protocol

An aluminium splint was placed over the subjects index finger to restrict movement at the inter-phalangeal joints. and secured with tape. A 3-axis digital accelerometer (Grove ADXL345, 200Hz) was then secured to the lateral aspect of the splint using tape. Subjects were instructed to tap the distal phalanx of the index finger (or as close as possible) with their thumb while keeping their forearm and hand in the prone position (Fig. 1). For the purposes of validation of the algorithm, touch sensors were applied to the contact surfaces of the index finger and thumb to provide a ground truth measure that accurately determined the occurrences of contact between the index finger and thumb. The output of the contact sensors was then compared to the output of the proposed TKEO algorithm to assess the accuracy of the algorithm.

Subjects were instructed to tap their index finger to their thumb in time with a metronome for a 30 second period. The metronome was set to five different frequencies (0.5, 0.625, 0.833, 1.25, 2.5 Hz). A final sixth trial consisted of un-queued tapping where subjects were instructed to tap as fast as possible without a metronome beat to follow.

C. Contact Time Detection Algorithm

To calculate the temporal occurrences of the contact and release events of the index finger and thumb during the finger tapping task, a combination of high-pass filtering using the MODWT and MRA as well as the detection of simultaneous changes in frequency and amplitude of the signal using the TKEO algorithm were implemented in a novel algorithm.

1) The raw accelerometer signal from the major axis of motion was filtered using a maximal overlap discrete wavelet transformation with a Haar mother wavelet. The Haar wavelet was chosen for its ability to accentuate high frequency and amplitude changes in a signal.

2) Following the wavelet transform, a multi-resolution analysis was performed to ensure zero-phase filtering of the processed signal as it is imperative to retain temporal resolution for this application. The MODWT acts as a series of zero-phase filters over the signal [11]. One very useful property of the MODWT is that it can be used to form a

multi-resolution analysis (MRA). A multi-resolution analysis allows for the reconstruction of the original time series signal into a sum of several new series, each of which is related to variations in the original signal at a given scale.

3) The first level (highest-frequency level) of the multiresolution analysis was then processed using the TKEO to further accentuate the high-frequency changes in the signal which corresponded to the contacts of the index finger and the thumb. The following formula [12] is used to compute a symmetric discrete time estimation of the TKEO where *Ts* is the sampling period and *n* is the sample number:

$$\Psi_n = \frac{2x_n^2 + (x_{n+1} - x_{n-1})^2 - x_n(x_{n+2} + x_{n-2})}{4T_s} \qquad (1)$$

4) To smoothen the signal before using a peak-finding algorithm to determine the contact-times, a moving maximum window followed by a moving mean window were used.

5) A peak-detection algorithm was then employed to find peaks in the smoothened and processed signal which correspond to the contact events between the index finger and the thumb.

6) Once the contacts were identified, a further peak finding algorithm was used to search between the peaks marking the contacts between the index finger and thumb to find the point of release of the index finger and the thumb.

D. Data Analysis

The data recorded from the participants were analysed using MATLAB (The Mathworks Inc., Natick, MA, USA). Since the major axis of motion during the task was along the Y-axis of the accelerometer (Fig. 1), the data from this axis was used to detect the events of the finger tapping task.

E. Validation

The contact times detected by the touch sensor were then compared to the times compared to the algorithm by calculating the mean error, sensitivity, specificity and accuracy. The mean absolute error can be calculated as follows:

$$MAE_{taps} = \sum_{k=1}^{k=N} \mid actual_k - detected_k \mid \qquad (2)$$

where N is the total number of contacts between the index finger and thumb in the given recording, actual indicates the contact as determined by the touch sensor and detected indicates the contact as determined by the algorithm.

$$Sensitivity = \frac{TP}{(TP + FN)}\%. \qquad (3)$$

Sensitivity was calculated as in (3). True positives (TP) were contacts that were identified by both the detection algorithm and by the touch sensors. False negatives (FN) were contacts that were not detected by the algorithm but were detected by the touch sensors.

Results

The mean absolute error and its standard deviation for both the contact and release times as well as the sensitivity of the detection algorithm are displayed in the following table.

TABLE I MEAN ABSOLUTE ERROR AND SENSITIVITY VALUES FOR THE CONTACT AND RELEASE TIMES AS DETECTED BY THE TKEO ALGORITHM RELATIVE TO THE TOUCH SENSOR DATA.

Frequency of Metronome (Hz)	Mean Absolute Error of Contact Times (ms)	Mean Absolute Error of Release Times (ms)	Sensitivity (%)
0.5	15.0 (9.6)	43.9 (61.7)	100
0.625	14.9 (7.5)	28.2 (36.5)	100
0.833	16.4 (7.6)	32.5 (40.7)	99.43
1.25	15.3 (6.5)	33.5 (46.2)	99.25
2.5	14.9 (6.6)	25.3 (35.4)	99.06
N/A	14.2 (4.8)	43.4 (31.3)	99.02

The results show that the algorithm is extremely sensitive to the finger tapping action as the sensitivity of the algorithm is greater than 99% for all conditions, with the lower tapping frequency conditions being the most sensitive. The mean absolute error of the algorithm is similar for all conditions which would suggest an inherent offset in the algorithms detection of the contacts.

For the release times however, the accuracy of the algorithm was lower. This is most likely a result of using the first level multi-resolution analysis signal. The first level MRA signal acts as a high-pass filter to the raw EMG signal, passing only the high frequency components. Since the opening action of the index finger and thumb is a relatively low frequency action, it may be more desirable to use a higher level of the MRA analysis to detect these more accurately. Depending on the frequency of the tapping action however, the particular MRA level that will detect the release action will change in an unpredictable manner making the accurate detection of the release events rather difficult.

Fig. 3 displays histograms that show the time shift of the detected contacts relative to the actual contacts as determined by the touch sensors. It is clear to see that for all conditions, most of the contacts were identified within 50ms of their actual occurrence.

Discussion

The finger tapping task is a common component of examinations of motor function in various motor disorders [2], [13]. It provides an estimation of the patients' capabilities of fine dexterity movements, which are often some of the first symptoms to appear in movement disorders such as Parkinson's Disease [14].

Instrumentation of the finger tapping task using inexpensive tri-axial accelerometers will increase the potential for the finger tapping assessment as it will allow for an in-depth analysis that is not possible using only a visual assessment. It will also provide objective results that will remove interrater variability that is inherently introduced by the current subjective visual examinations [2], [15].

During the finger tapping task, the contact instance of the index finger with the thumb is represented by a simultaneous increase in the instantaneous amplitude and frequency of the acceleration signal recorded from the tip of the index finger. Using this knowledge, it is possible to make use of the Teager-Kaiser energy operator along with the maximal overlap discrete wavelet transform as a form of high-pass filter to accurately detect the temporal occurrences of the contact events. Although the TKEO has previously been used in a number of applications [8]–[10], its use in conjunction with the MODWT for the detection of finger tapping events from an accelerometer signal has not been previously explored.

A novel algorithm was developed that uses MODWT in conjunction with the TKEO to detect the temporal events of the finger tapping task. The algorithm was validated using ground truth data recorded from touch sensors placed on the contact surfaces of the index finger and the thumb. The performance of the algorithm was evaluated using the mean absolute difference, its standard deviation and the sensitivity measure for both the contact and release times. The results of the evaluation show that the algorithm was able to positively identify at least 99% of the contacts between the index finger and the thumb under each of the finger tapping conditions that were tested.

The mean absolute difference of the contact times were 14.7 ± 6 ms over all of the finger tapping conditions examined. The mean absolute difference for the release times however, were less accurate (36.5 ± 36.3 ms) for a number of reasons.The filtering process using the MODWT decomposes the signal into a number of "levels", each level effectively acting as a band-pass filter with decreasing centre frequencies on the signal. The first level therefore contains the highest frequencies in the signal. As the release action of the finger tapping task is a relatively low frequency event compared to the contact action, it may be represented more accurately by a higher level decomposition of the MODWT. Due to the changing frequency of tapping in the various conditions that were tested, it is difficult to choose an appropriate level that consistently contains the release events.

Further analysis involving both older healthy and older populations affected by movement disorders will be required to validate the use of this algorithm during episodes of tremor, chorea or other unintentional movements. The results of the validation of this algorithm suggest that it is possible to identify the temporal events of the finger tapping task in an inexpensive, objective and accurate manner using only a tri-axial accelerometer.

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Figures

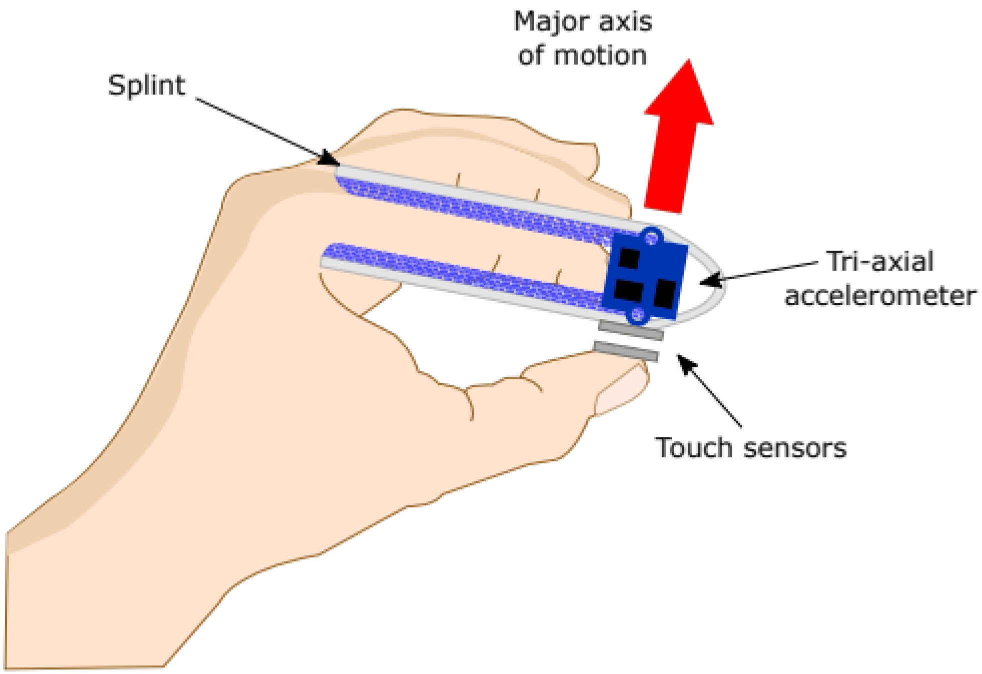

Fig 1: Illustration of the experimental set-up. A splint is attached to the subject’s index finger. An accelerometer is then attached to the lateral aspect of the splint. Touch sensors were placed on the contact surfaces of the index finger and thumb to provide ground truth data for the contact times.

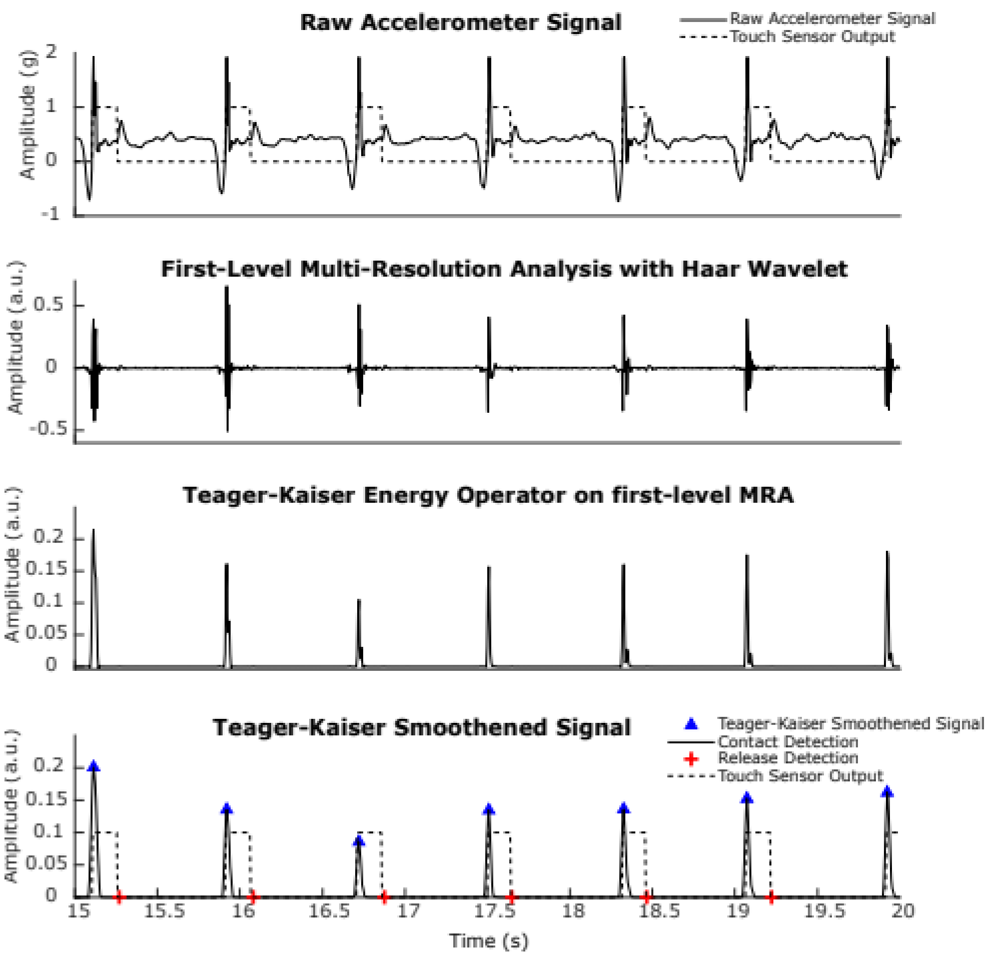

Fig 2: Processing steps of the raw accelerometer signal to the final TeagerKaiser Energy signal that is used to determine the contact instances during the finger tapping task.

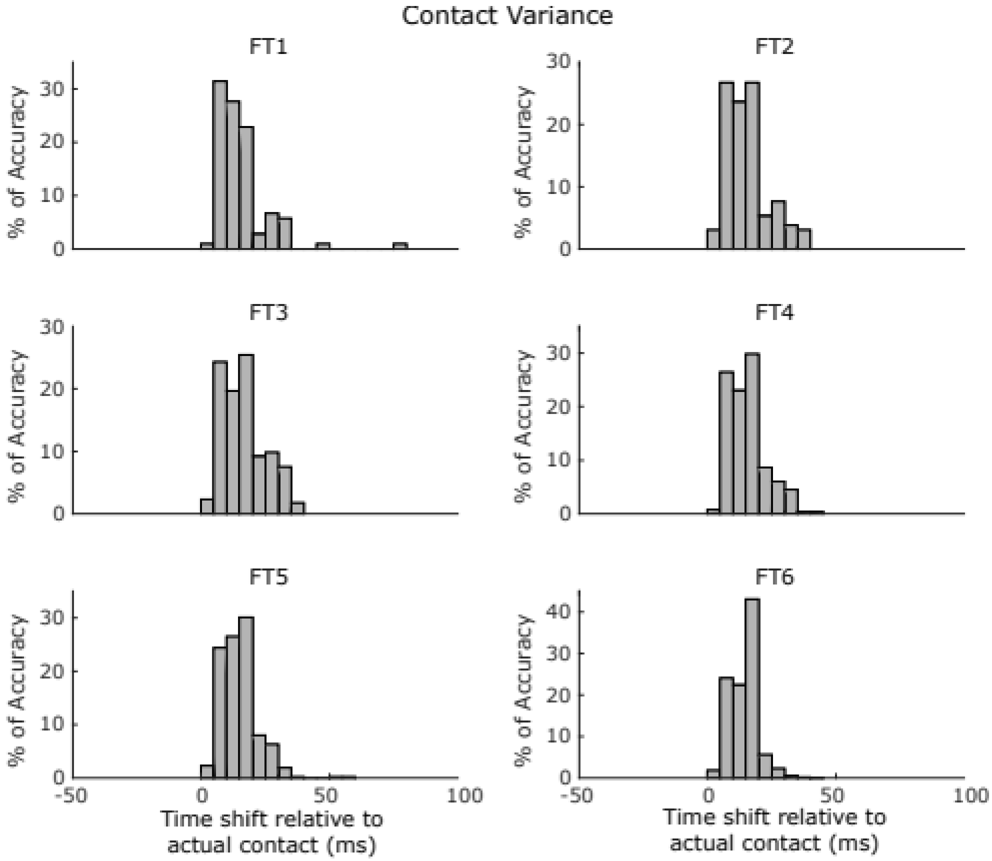

Fig 3: Histograms showing the distribution of the difference in detected contact times vs the actual contact times as determined by the touch sensors.

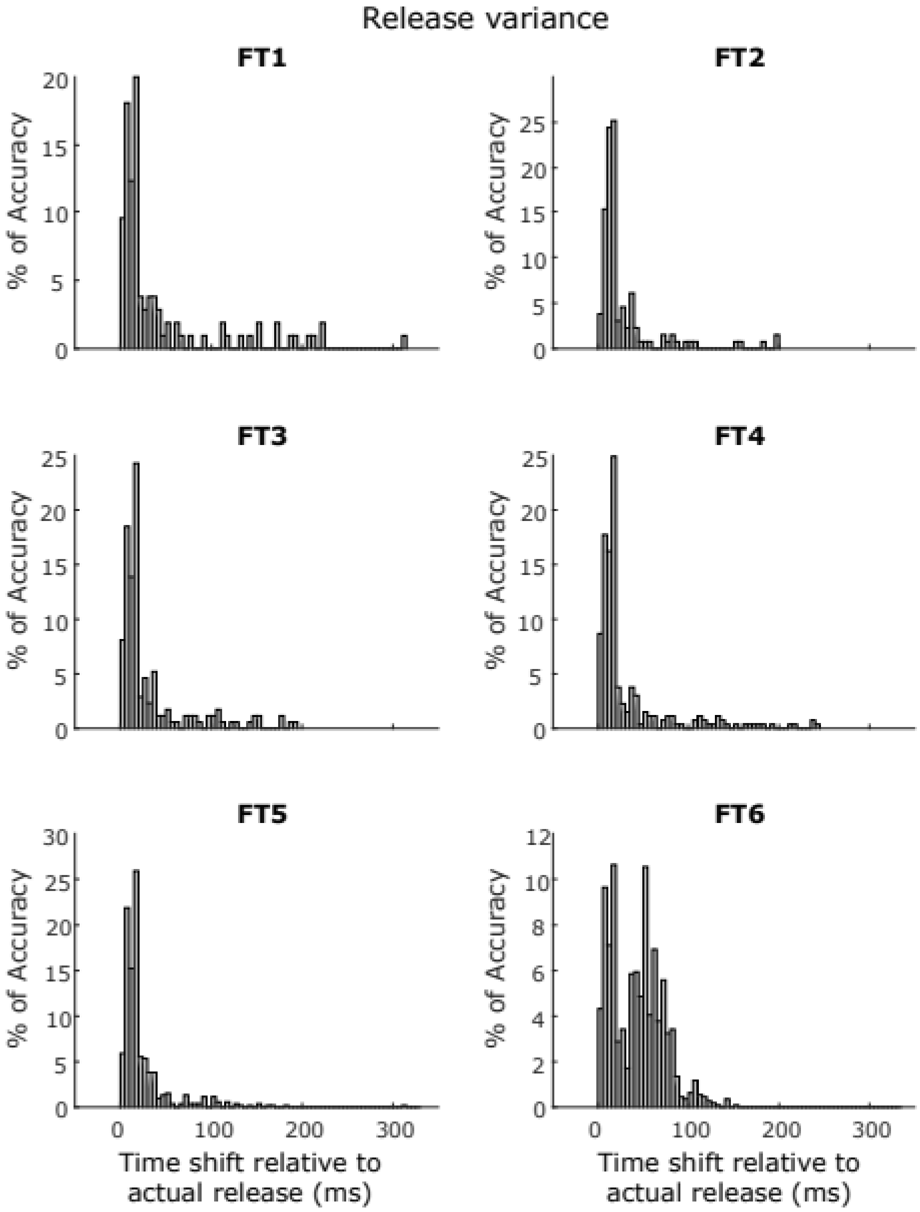

Fig 4: Histograms showing the distribution of the difference in detected release times vs the actual release times as determined by the touch sensor s.

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