

# Whose Move is it Anyway? Authenticating Smart Wearable Devices Using Unique Head Movement Patterns

**Abstract**—In this paper, we present the design, implementation and user studies of a novel approach to authenticate wearable devices users based on their unique behavioral patterns. We prototype an authentication system, dubbed *Headbanger* for head-worn wearable devices by monitoring user’s unique head-movement patterns in response to an external audio stimulus. Solutions today primarily rely on indirect authentication mechanisms through the user’s smartphone, which can be cumbersome and more susceptible to adversary intrusions. Biometric solutions, are subject to the availability of the specific sensors in the wearable unit. Using a head-worn personal imaging device as a running example and through extensive experimental evaluation with 30 human subjects, we show that our mechanism can authenticate users with an average acceptance rate of 95.1% while keeping the average false acceptance rate of 3.9%.

## I. INTRODUCTION

Wearable devices are now available off-the-shelf and on the way to become an integral part of human lives [1], [2], [4]. This is thanks to the advances in hardware miniaturization technology, affordable sensors and processor chips, and low-power computing. The wearable devices typically collect data about their wearer and their surroundings. This collected data on such devices is personal in nature and often relates to the user’s health. There has been work on limiting privacy threat to other users [28], [29], [33]. Any security solution for these devices has to strike an appropriate balance with user convenience, especially as users are interacting with an increasing number of such specialized devices. A fundamental building block for safeguarding the security of user data acquired on or accessed through wearable devices are user authentication techniques.

**Authentication Challenge.** Authentication on most commercially available wearable devices today [1], [4] relies on an indirect mechanism, where users can log in to their wearables through their phones. This requires the wearable device to be registered and paired to the user’s mobile device, which makes it inconvenient as the user has to carry both devices. The security of this approach is also in question as it increases the chance of hacking into both the devices if either of those are lost or stolen. Some devices including Google Glass [2] and FitBit’s health tracker [1] allow linking the device to online accounts instead of the phone for user’s convenience. This, however, does not add any security. Indirect authentication remains a dominant paradigm for wearables despite these fundamental shortcomings because these devices are *seriously resource-constrained* in many aspects: battery power, computational and storage capabilities, and input/output methods.

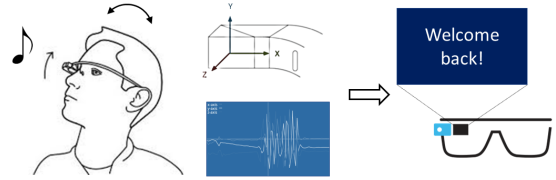


Fig. 1. Illustration of Headbanger. The head-worn device authenticates the users based on signatures generated from head-movement patterns. These patterns are created in response to an audio snapshot played on the device.

As a result, typical authentication methods designed for more powerful devices can not be directly applied and must operate indirectly through a paired smartphone or other more capable device. In this paper, however, we take the viewpoint that wearables will become more independent units that have to maintain security guarantees without such paired devices and we seek to develop suitable *direct authentication* methods that are both accurate and light-weight.

Before we explore direct authentication methods for wearable devices, let us first consider the available solutions for other mobile systems, especially smartphones and tablets. Broadly speaking, the two most commonly used authentication methods on mobile systems are (arguably) password-based methods (with their variants) and biometric-based methods. However, we argue that neither of these two methods is really suitable for wearable devices. Typing passwords or drawing swipe patterns on wearable devices can be quite cumbersome due to their small input/output units, if they do have a touch sensor at all. Collecting and recognizing physiological biometrics (such as DNA, fingerprint, hand/finger geometry, iris, odor, palm-print, retinal scan, voice, etc.) requires specialized sensing hardware and processing resources that add cost, and many of these sensors are larger than the size of wearables themselves.

We therefore focus on a third class of direct authentication methods: relying upon the uniqueness of human behavior characteristics such as human walking gait, arm swings, typing patterns, body pulse beats, eye-blinks, etc. This way of authenticating users is often referred to as *behavioral* biometrics,

and existing work has largely studied it in the context of authenticating smart phones and tablets [9], [15], [16], [34], [38], [40], [41], [47]. The main advantage of using behavioral biometrics for mobile devices is that the signatures can be readily generated from raw data of built-in sensors such as motion sensors, camera, microphones etc. Considering that cameras and microphones, as well as vision and audio processing algorithms, are quite energy-hungry, we thus focus on those behavioral biometrics that can be easily captured by sensors that require less power consumption, such as accelerometer. *More specifically, we propose to authenticate wearable devices to users based on one type of behavioral characteristics: our unique body movement patterns and their dependence on external stimuli that wearable devices can generate, such as vibrations and music.*

**Head-movement based authentication.** Body movement patterns have long been used by humans to discriminate between people. By watching how a person walks, dances, waves hands, we can often recognize the person from afar. This is because human body movements are usually *distinctive* and *repeatable*. Achieving the same through wearables, however, is not straightforward and poses significant research challenges: it is unclear whether these seriously-constrained devices are able to capture the movement patterns, process the data, and quantify the uniqueness of each user's behaviors. Moreover, each device will have only a limited view of body movements, dependent on its mounting position on the human body. In this paper, we set out to conduct a holistic study of wearable authentication through body movements and to design an accurate, robust and light-weight authentication system. A key distinguishing feature of our work is that we will also consider stimuli that wearable devices can provide to design challenge-response inspired mechanisms, particularly stimuli that are difficult to observe even for the closest adversaries. For example, we can use fast-tempo music through earbuds to stimulate movements and to make such free-style movements more repeatable.

In particular, we have designed, implemented and evaluated *Headbanger*, an authentication system that generates a signature from user's head-movements. These signatures are used as the behavioral biometric. To ensure that the user is proactive in making head-movements we stimulate the process by playing a short duration audio track with fast beats. The user in response to the rhythm and beats makes head-movements that are captured by the accelerometer and processed to generate and authenticate the user's unique biometric signature. Although we use a Google Glass a running example for the wearable device, our design can be applied to other head-worn gadgets and any system that can record head-movements through motion sensing. Our choice for using head movements is motivated by the fact that head-worn wearables are becoming very common today and such devices are already equipped with motion sensors; for example, personal imaging and heads-up display devices, gaming headsets, artificial intelligence devices.

In summary, the key contributions of this paper are:

- 1) We have designed and implemented a novel user authentication method to wearable devices using head-movement

patterns. Our study shows that user's head-movement patterns contain unique signatures that when inferred correctly can be used as valid behavioral biometrics for authentication. We design a system, *Headbanger*, that records, processes, generates unique signatures, and classifies head-movement patterns of users based on the accelerometer (inbuilt on the wearable device) sensor readings.

- 2) Through comprehensive experiments involving multiple users and over different system design parameters we show that head-movement patterns can be used as a behavioral biometric. Our approach effectively identifies a wearable device user, with average false acceptance rate of 3.9% and an average true-positive rate of 95.1%.
- 3) We implement *Headbanger* on Google Glass and carefully profile the execution time of each software module in the implementation. Our measurements indicate an average response time of 4.4 seconds on the Google Glass for the most accurate results.

## II. BACKGROUND

### A. Mobile Device Authentication Through Body Movements

Recently, a number of body-movement based authentication approaches have been proposed for mobile devices, in which unique signatures from human behavior (subconscious or in response to external stimulus) provide cues for differentiating and authenticating users. For example, it has been shown that gait (e.g., stride length, the amount of arm swing) when the user is walking or running is a reliable identification cue, and irrespective of the environment [47]. Okumura et.al. [40] have shown that human arm swing patterns can be used to create signatures to authenticate to their cell-phones. Monroe et.al. [38] show that keystroke rhythms, when users type on the keyboard, that include typing dynamics such as how long is a keystroke, how far is between consecutive strokes, and how is the pressure exerted on each key, can be used to authenticate users. Similarly, mouse usage dynamics [34] and touchpad touching dynamics [9], [16] have also been shown to serve as potential authentication cues.

We take the viewpoint that, in comparison to other means of authentication, body-movement based authentication offers great convenience – with increasing access to built-in sensors on wearables, it has become possible to generate and infer unique behavioral signatures specific to users. With this rationale, we design an authentication system, dubbed *Headbanger*, for head-worn devices by monitoring user's unique head-movement patterns in response to an external audio stimulus.

### B. Using Head-movement for Authentication

According to Jain et al. [32], a type of body movement can be considered for the authentication purpose as long as it is *universal*, *distinctive*, *repeatable*, and *collectible*. With the advancements in head-worn wearable computer designs, collecting head-movement patterns using built-in accelerometers and motion sensors has become increasingly accessible. Such sensors are available on most of today's head-worn wearable

devices, thus making head movements both *universal* and *collectible*.

In this paper, we strive to show that free-style head movements are reasonably *distinctive* and *repeatable*, especially when combined with external stimuli such as music beats. In *Headbanger*, music plays a crucial role in stimulating body movements such that the resulting movement pattern is natural to the user (more distinctive) and easier to remember (more repeatable). It has been shown [52] that most people move their body as a natural response to external rhythmic stimuli such as music; even at a very early age, infants respond to music and their movements speed up with the increasing rhythm speed. Most adults naturally perform head movements or hand movements when listening to a fast beat audio track. When combined with external rhythmic stimuli, we believe body movements become more distinctive – not only a person’s movement pattern is unique, but their response to rhythmic stimuli is also unique. In this way, the resulting authentication system will be more dependable.

Based on a preliminary analysis of the accelerometer signals from three Google Glass users, we observed (see Figure 2 (a)-(c)) that these users *repeatedly* showed *distinctive* head-movement patterns (that are differentiable even through simple signal processing techniques), when listening to the same music beats.

Next, we conducted a preliminary experiment to further investigate whether head-movement patterns can be potentially used to authenticate users. In this experiment, we collected head-movement accelerometer data from 28 subjects, wherein each subject was asked to perform a simple nodding movement following the music cue, as shown in Figure 14(a). \*\*\*YZ: refer to one of the figures we have in the results section\*\*\* For this purpose, we examined two simple features: (1) wave amplitude, the difference between the bottom of a wave and the peak of the following wave, which indicates how hard a person nods; and (2) response time, the time interval between a music beat and the corresponding nodding motion, which indicates how quickly a person responds to music beats. \*\*\*YZ: please use a wave picture to show what are these three features \*\*\*

Figure 3 shows each subject’s wave amplitude box plot (we collected 20 nodding samples for each subject in the experiment). We observe that each subject’s wave amplitude distribution \*\*\*

Next, we calculate the similarity between response times of different users. We take the response time time series of each subject, calculate the average Cosine Distance (COS), Correlation (COR), and the Dynamic Time Warping (DTW) [?] output between any pair of subjects, and plot these results in Figures 4 (a)-(c). In each plot, we show the distance values for all 28 subjects – for each subject, we plot distances between her own response time time series and other 27 subjects’ response time time series (referred to as distances with false subjects, shown in blue dots), as well as distances among her own response time time series (referred to as distances with true subjects, shown in red dots). All three figures show that distances within a subject’s own response times are clearly smaller than those across subjects.

These observations suggest that even with simple nodding

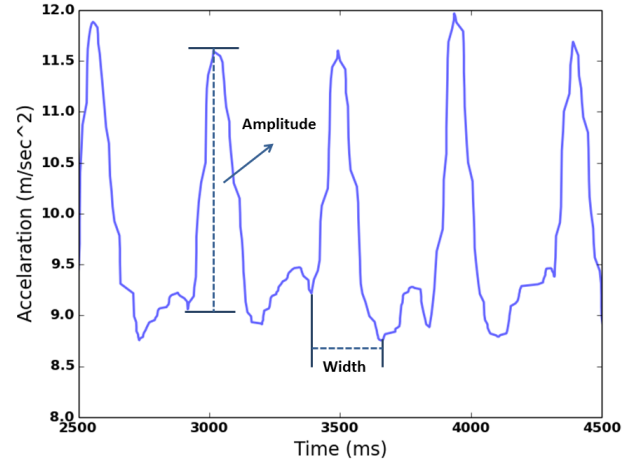


Fig. 3. Waveform with beats snapshot.

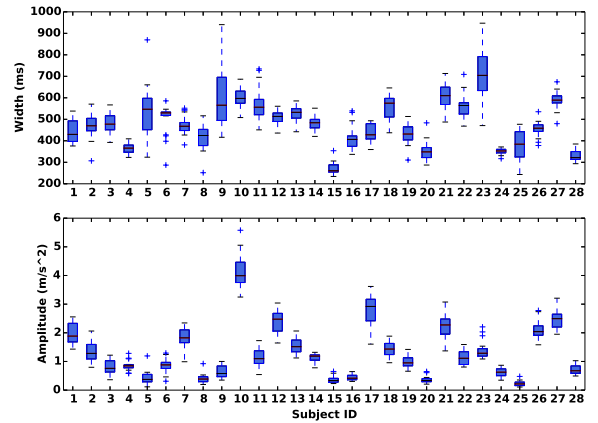


Fig. 4. Wave Amplitude Boxplot \*\*YZ: please re-consider the features\*\*

movements, the accelerometer data collected by Google Glass have the potential to be used as authentication means. With this motivation, we next devise the authentication protocol for *Headbanger*.

### III. HEADBANGER SYSTEM DESIGN

In this work, we design a system, *Headbanger*, that will enable direct authentication of users to their smart-glass device using head-movements. The authentication process has two phases: a offline training phase and an online authentication phase. In the training phase, the system collects the real user’s head movement data and use them as conducts the training to extract the features. We refer to this set of features extracted through the training process as the *trained* dataset which essentially serves the purpose of a reference in the matching stage. In the following discussion, we assume there is only one real user for the device for the sake of simplicity. An extension to support multiple users per device will be possible

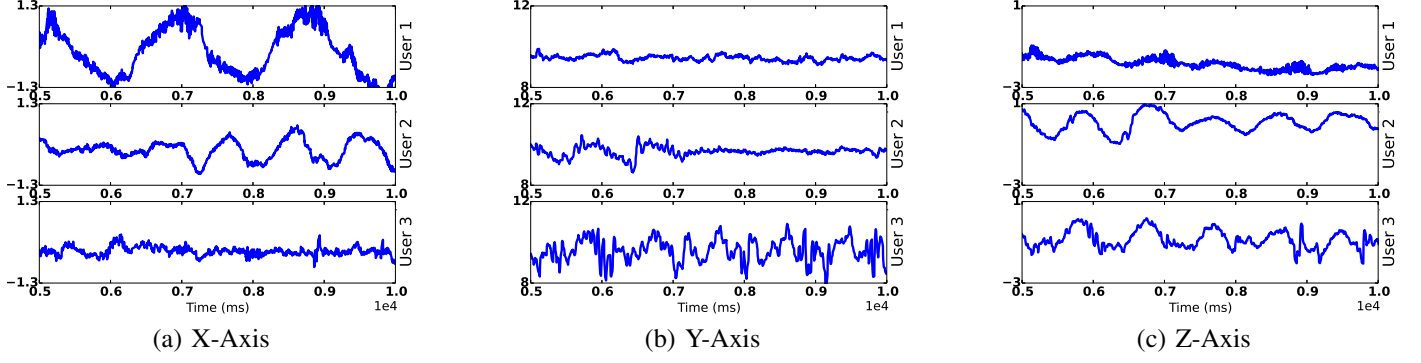


Fig. 2. These plots show the raw accelerometer data in the time domain for five different users when they move their head in response to the same music track wearing the same Google glass. The plots indicate that different users' head movement patterns appear distinctive from each other. The three users wore a Google Glass (in turns) and listened to a 10 second audio snapshot of a pop song.

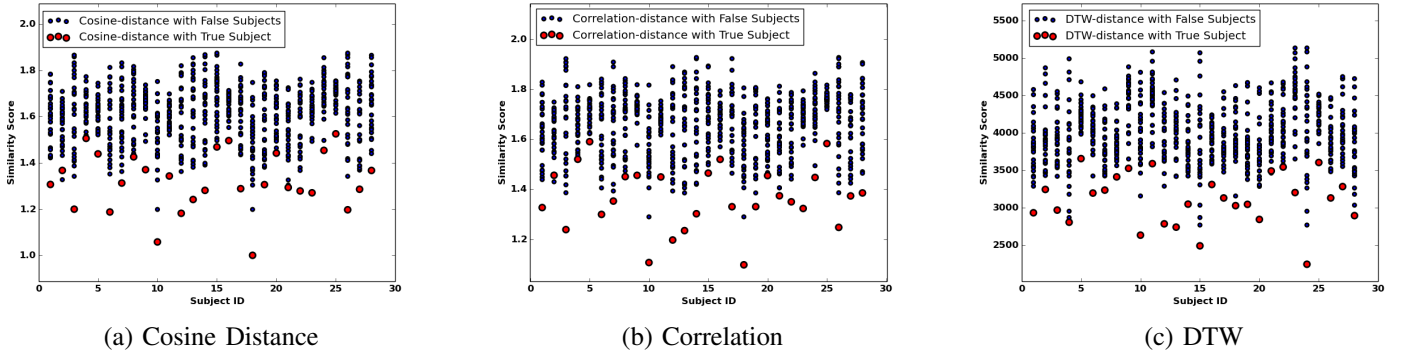


Fig. 5. The similarity score is computed over  $N$  ( $N = 20$ ) sample data for each subject, and 28 subjects in total. For each column, a red dot represents the average similarity score of that subject's own SRT, i.e., each of his sample data compared with the other  $N-1$  SRTs from him, hence we have the average similarity score over all these comparison. Similarly, a blue dot on the same column represents the similarity score of that subject's SRTs compares with another subject's SRTs.

with minor modifications, namely, by appropriately indexing the users in the trained database.

In the online authentication phase, the sensor readings during the authentication attempt are processed, features are extracted, matched with the trained set. The user is authenticated upon a successful match. We posit that *Headbanger* will run as a service in the device upon power-up or application start-up, similar to the screen-lock in smartphones. The authentication process is initiated by playing a short duration audio track on the device, to which the user responds through head-movements. Our design is developed based on the idea that humans respond to music naturally through head movements, and that such movements are more significant and unique when the track contains fast beats and/or rhythm. We will refer to the audio snapshots as *music cues* in the rest of the paper. *Headbanger* generates unique features from the head movements of a user, and uses them as a unique signature for identifying the right user of the device. The system will grant access only when the head-movement signature generated during the login attempt matches with the original user's signature.

As illustrated in Figure 5, the user authentication in *Headbanger* involves the following key processes:

- *Sensor data collection*: *Headbanger* records the head-movements in the form of raw accelerometer signals (in 3 dimensions) using the inbuilt accelerometer sensor on the smart-glass device.
- *Filtering*: The accelerometer signals are filtered by applying a low-pass filter to remove records of extraneous motion.
- *Parameter generation*: The accelerometer signals are processed through the dynamic-time warping (DTW) tool [7] to obtain a DTW feature that is treated as the unique signature for the user.
- *Classification*: The signatures are classified as a match or not a match, based on a thresholding scheme and using the trained data set as a reference. The system grants the user access to the device if there is a match with sufficient confidence.

We will now discuss these design aspects in more detail.

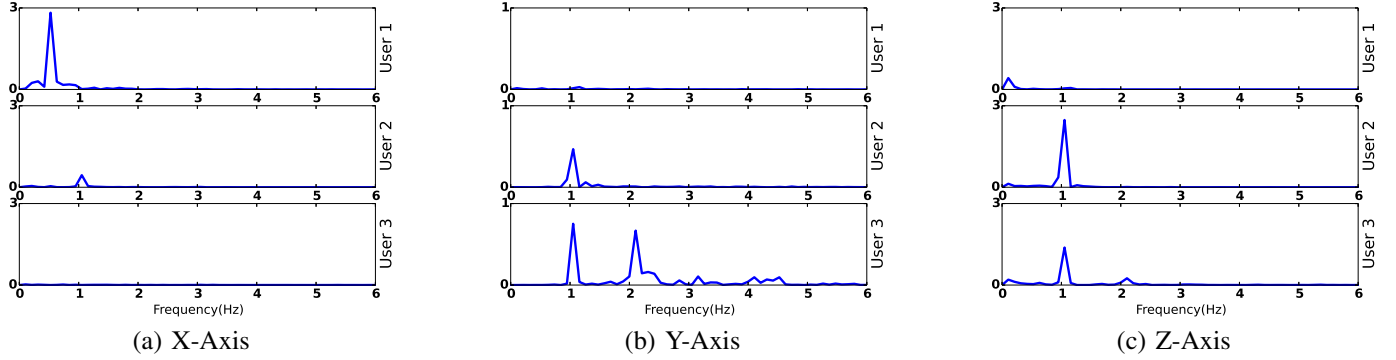


Fig. 7. Accelerometer data from three users, in the frequency domain. The data show that the spectrum is significantly concentrated within 5Hz for all three users.

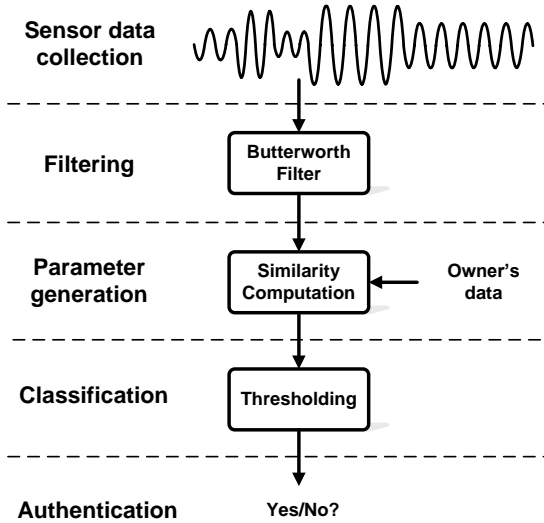


Fig. 6. *Headbanger* system design flow. The online authentication phase of *Headbanger* consists of the following steps: (1) sensor data collection in which we collect accelerometer data while users move their head as a response to an audio track played on the glass, (2) filtering in which we apply a Butterworth filtering to smoothen the sensor data for subsequent processing, (3) parameter generation in which we calculate the dynamic time warping (DTW) distances between two accelerometer samples as the parameter, and (4) classification in which we adopt an adaptive thresholding mechanism to classify the user's head movement, whose output will be used as the authentication result.

#### A. Sensor Data Collection

The sensor data collection step involves the user wearing the head-worn device and making head-movements in response to the music beats played on the device for a stipulated duration of  $T$  seconds. In this duration, the raw accelerometer signals, from the inbuilt sensor, are collected at a sampling rate of  $r$  samples/sec; the default sampling rate on Google Glass is 50Hz. The accelerometer data corresponding to one user, is a collection of accelerometer readings on the 3D axis (x, y, and z) collected over  $T$  sec duration. Figure 1 illustrates the axis conventions with respect to the user's head position. The data

collection unit stores the accelerometer readings in a matrix with dimensionality  $3 \times rT$ , where each element corresponds to one signal point. We will refer to this  $3 \times rT$  as a *sample* in our design. We retain the duration  $T$  to be in the order of few seconds, as frequency of human head movements are, intuitively, typically in the order of few times per second. This intuition will be more clear from the filtering stage to be discussed next.

#### B. Filtering

The accelerometer samples are cleaned-up from noise (accelerometer readings due to spurious movements such as vibrations) through a filtering stage. The filtering ensures that the head-movement signature generated from the accelerometer readings encompasses only head movements, and not any spurious signals caused due to vibration or shaking. From the frequency spectrum of each accelerometer sample, as shown in Figure 6 for three users, we can observe that the spectrum is significantly concentrated within 5Hz. We note that music tracks with high tempo, or fast beats, typically contain beats in the order of the order of hundred beats per minute. In particular, the high tempo music that we used in our experimentation was contained 94 beats per minute [37]. We infer that the head-movement, in response to the beats, will be of the same order. Hence, we hypothesize that the signal spectrum in [0,5] Hz range encompass human head movements; where 0 Hz can indicate that the head is steady still, and 5 Hz can correspond to a vigorous head-shake. We filter accelerometer samples using a low-pass digital Butterworth filter [12]. We set a relaxed cut-off frequency of 10Hz. Even with the relaxed cut-off, the filtering results in clean accelerometer samples with head-movement patterns that are prominent and detectable. Figures 7 (a)-(c) show the filtered results of the raw accelerometer samples shown in Figure 2; compared to raw data, the filtered results are much more suitable for subsequent processing.

#### C. Signature generation

We generate a signature from the accelerometer signals using the dynamic-time warping (DTW) tool [7]. DTW is



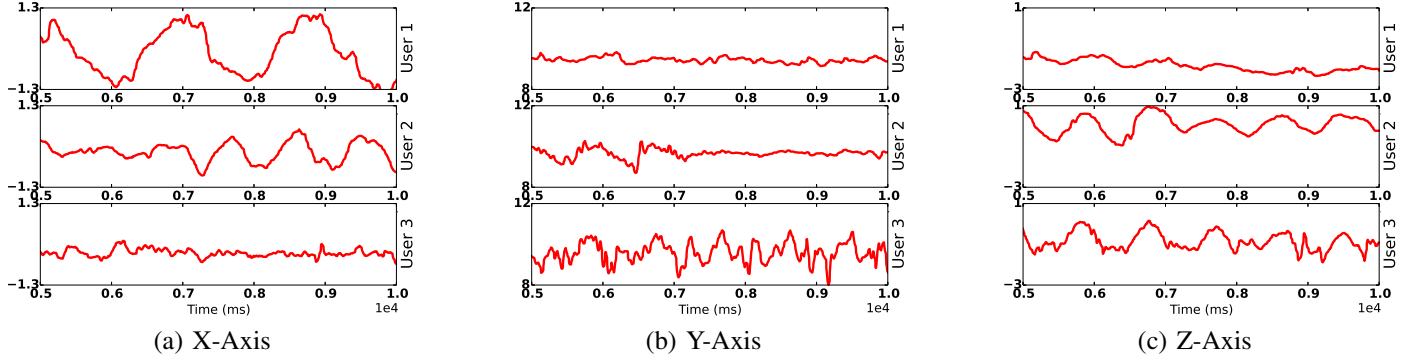


Fig. 8. Filtered accelerometer signals. Applied Butterworth filter of order 2 and cut-off frequency 10Hz.

generally used as a similarity matching tool for time-domain analysis of temporally varying signals. DTW compares a temporal signal with a reference (temporal) signal over a certain time-window and yields a distance measure as the score. A low score (DTW distance) implies that the test signal is in close match with the reference. We use the DTW to generate a signature for the head-movements from the accelerometer signal. We observed from our preliminary tests that, users often start head movement at an angle with the vertical which varies among users. However, we also observed that the head-movements that follow exhibit a consistent, and often periodic, patterns over time. Treating the accelerometer sample set from the first trial as a reference, we apply the DTW algorithm on the successive accelerometer sample set to obtain a distance score vector,  $\hat{d} = (d_x, d_y, d_z)$ ; the three elements in  $\hat{d}$  denote the DTW distance score in the  $x, y, z$  axes, respectively. By computing the mean of the distance scores obtained for each accelerometer pair we generate the mean-value DTW distance, which is treated as the head-movement signature or unique *feature* for that particular user and audio combination.

In the offline training phase, we conduct  $M$  trials of head-movement exercises, collect  $M$  training samples, and obtain  $M - 1$  reference distance vectors. We observed from our evaluations (to be discussed in the next section) that  $M = 30$  can yield in high accuracy while  $M = 10$  can yield reasonable accuracy. The trade off is the computation overhead that goes into conducting the training (primarily DTW computations) for the  $M$  samples.

#### D. Classification

The classification step labels a test sample based upon the pre-established training/reference samples.

In this study, we developed a simple yet effective classification scheme based on adaptive thresholds. We highlight the aspects of the adaptive thresholding procedure as follows:

- 1) Given  $M$  training samples, we identify the top  $K$  samples that have the lowest  $K$  average distance to the rest of the training set, and calculate their DTW vectors to the rest of the samples in the training set to obtain  $(M - 1)K$  distance vectors. We call this resultant vector as Top- $K$  reference distance vector. For example, if  $K = 1$ ,

then we call the resulting algorithm as Top-1 algorithm; if  $K \neq 1$ , then we call the resulting algorithm as Top- $K$  voting algorithm. The voting refers to the procedure that the DTW computation results for each sample in the training set is referenced, sorted (in increasing order of DTW scores) and the classification (a binary index, match or no-match) is performed on the top  $K$  entries. The final classification result corresponds to the majority vote from the list of  $K$  results. By using top  $K$  samples, instead of all  $M$  samples in the training set, we significantly reduce the computation overhead in the authentication process. In our evaluation, we will study the impact of  $K$  value; in particular, we evaluate for  $K = 1$  and  $K = 3$ .

- 2) Compute the 3 element  $(x, y, z)$  axis mean  $\mu$  vector and standard deviation  $\sigma$  vector of the top- $K$  distance vector, for each authentication trial. We define “true” range as  $[\mu - n\sigma, \mu + n\sigma]$ , where  $n$  is a design parameter that will be fixed by the designer. The samples outside this range are labeled as “false”. We refer to this range  $[\mu - n\sigma, \mu + n\sigma]$  as the threshold in our classifier design, and the strictness of this threshold is characterized by the value of  $n$ ; a large  $n$  relaxes the threshold but can increase the false acceptance rate while a strict threshold with small  $n$  value can result in a high rejection rate of true samples. In our system we aim to reach an optimal value of  $n$  that can result in acceptable accuracy.

If the user’s data is classified as “true” then the user is authenticated to the device; otherwise, the user is rejected.

## IV. EVALUATION

We evaluated *Headbanger* with comprehensive laboratory studies involving human subjects. We collected from volunteer participants accelerometer sensor readings with Google Glass. We analyzed these traces offline on a PC. Our evaluations are primarily aimed at determining the accuracy of detecting and differentiating users based on their head-movements, and understand the effect of design parameters such as similarity metric, length of the music cue and training data-set size and sampling rate on accuracy. We also measured the response time of our Google Glass implementation of *Headbanger*. Our

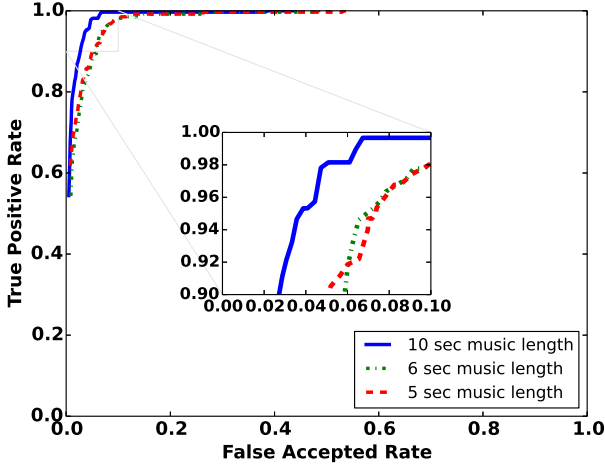


Fig. 9. Evaluation of impact of music cue duration on TPR and FAR in Top-1 scheme ( $K = 1$ ). A 10 sec music snapshot is trimmed into music cues of 10 sec, 6 sec and 5 sec correspondingly. The variable here is  $n$ . Each (TPR, FAR) data point in the curve corresponds to a different value of  $n$ .

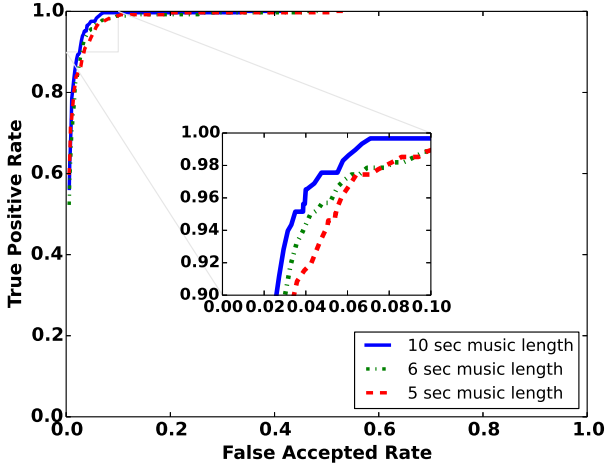


Fig. 10. Evaluation of impact of music cue duration on TPR and FAR in Top-3 voting scheme ( $K = 3$ ). A 10 sec music snapshot is trimmed into music cues of 10 sec, 6 sec and 5 sec correspondingly. The variable here is  $n$ . Each (TPR, FAR) data point in the curve corresponds to a different value of  $n$ .

studies were approved by the Institutional Review Board (IRB) of our institution.

#### A. Is it Accurate?

1) *Participants*: We had total of 30 volunteer participants for this experiment. The participants list included a total of 19 males and 11 females. The average age of the participants was 29.7 years with a standard deviation of 9.81 years. The youngest participant was 23 years old while the eldest was at 54 years.

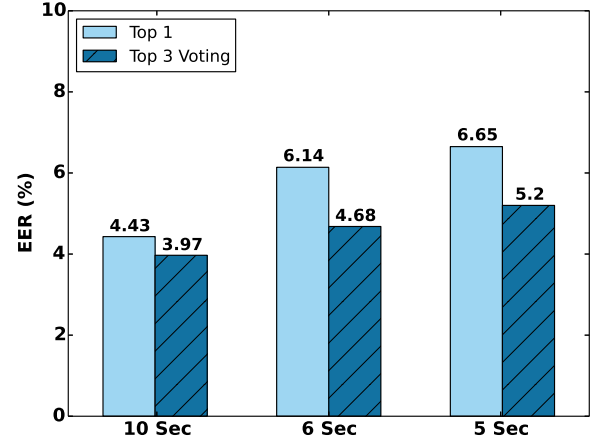


Fig. 11. Comparison of EER for different music lengths (10 sec, 6 sec and 5 sec) with a fixed  $n$  value of 2.7

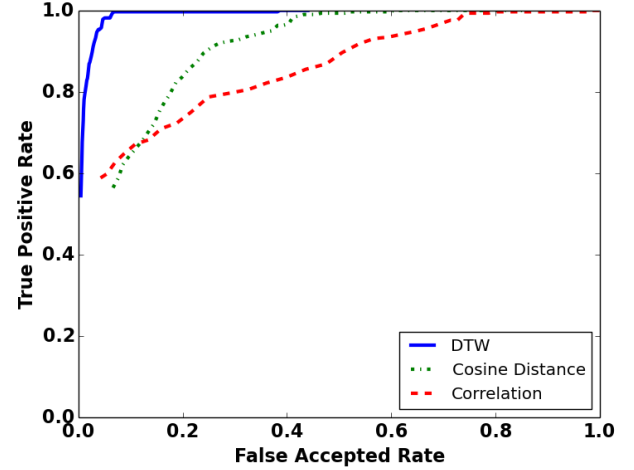


Fig. 12. Evaluation of impact of different distance metric (DTW, cosine distance, and Correlation). Although DTW is relatively computing-intensive, ROC curve indicates that DTW provides a large enhancement over the other two metrics.

2) *Procedure*: Our first experiment setup aimed at emulating the typical usage scenario of *Headbanger* for authentication, where a user conducts head-movements in response to a music cue played on the Google Glass device during a login attempt. In this experiment, all participants were asked to wear a Google Glass device. Participants who originally wore spectacles were asked to remove their spectacles before conducting the experiment. The trials were conducted in an academic environment and overseen by one of our team members. The Google Glass ran our data-collection app that played a piece of music (music cue) for a specific duration, and recorded the accelerometer sensor readings. We conducted these trials for three duration values: 5 s, 6 s and 10 s. As we will show

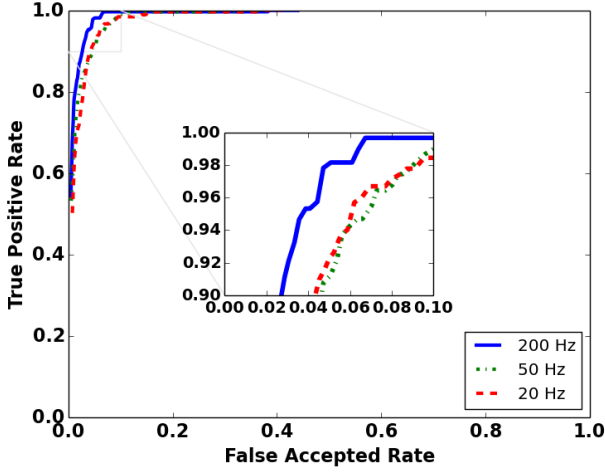


Fig. 13. Evaluation of impact of different sampling rate shows that the highest sampling rate 200 Hz gives the best result. However, the sampling rate determines computational effort for the smart device, which could be significant in terms of response time.

further, the accuracy of the system can significantly improve with the duration of the music cue; longer the duration better is the accuracy. The sensor readings were recorded into a text file that was stored in the Glass's memory and later transported to a PC for offline processing through a Python script. The experiment was conducted in a well-lit indoor academic laboratory environment.

During the course of the experiment, the participants were allowed to take a break or withdraw from experimentation if they felt uncomfortable at any point; for example, feeling dizzy after head-movement for a period of time, not being able to see clearly if near-sighted, etcetera. The conductor also allowed the user to take a break of about one minute after each experiment trial. Each trial lasted for the duration of the music cue played on the Glass, and a total of 40 such trials were conducted for each of the 30 subjects. The experiment lasted over a duration of 60 days, of which 15 subjects conducted their trials in a single sitting over a period of two hours, while the rest of the trials were spread over 3 days on an average per subject. The experiment yielded three sets of data traces that each correspond to the three music cue durations we selected.

3) *Results*: We evaluate the accuracy of *Headbanger* using metrics that are commonly used in evaluating authentication systems, namely, the false acceptance rate FAR (percentage of false test samples that are mistakenly accepted), false rejection rate FRR (percentage of true test samples that are mistakenly rejected), and true positive rate TPR (percentage of true test samples that are correctly accepted). A strict threshold in the classifier can lead to high FRR, while overly relaxing the same can lead to a high FAR. Hence, we also consider the equal error rate EER (percentage of errors when  $FAR = FRR$ ), that considers both FAR and FRR. Figures 8, 9 and 10 report the accuracy of *Headbanger* through the metrics stated above. In general, our evaluation of the 30 subject data-set indicates

that a TPR of 95.1% at FAR of 3.5%, and  $EER = 3.97\%$  can be achieved in *Headbanger*, however, these results are tailored to the following parameter and algorithm choices: 10 sec music duration,  $K = 3$ , and 30 (out of 40) trials from each user being used for training with a thresholding parameter value  $n = 2.7$  with DTW. We will now discuss the results and the impact of such parameter choices on accuracy in more detail.

4) *Impact of similarity algorithm*: In previous preliminary study, we find that DTW, Cosine Distance, and Correlation are giving promising results for the response time sequence, hence we will evaluate these three algorithms in our end-to-end system. Also due to DTW is relatively more computing-intensive than the other two algorithm, we would like to see whether DTW is worth of computing resource. In this experiment, we vary thresholding parameter value  $n$  and fix the other parameters: 10 sec duration,  $K = 1$ , and training data size = 30. We can observe from the ROC (receiver operating characteristic) curves in Figure 11 that DTW gives the best result among three algorithms, since its curve is the closest to the upper left corner. Our system preserves all characteristics of the data, which includes the response time to the music beat and the 3-axis accelerometer data. In terms of matching the waveform of two signal, DTW can achieve significant enhancement than the other two algorithms [?].

5) *Impact of music cue duration and  $K$  value*: The classification algorithm in *Headbanger* generates the classification result (YES or NO) by voting among the individual results each generated by the top- $K$  samples in the training set. We can observe from the ROC curves in Figure 8 and 9 that for both,  $K = 1$  and  $K = 3$ , the TPR is close to 95% while the FAR is slightly above 3% for the 10 sec music duration. For  $K = 1$  the FAR increases to about 7% for the 5 sec and 6 sec cases, however, for  $K = 3$  the FAR decreases to about 3% and 4%, respectively. We observe a similar trend with the EER as shown in Figure 10, where improvements of 0.5 - 1% can be achieved by choosing  $K = 3$  over  $K = 1$ . This indicates that the accuracy in *Headbanger* can improve with a larger value of  $K$ . However, the improvement in accuracy through redundancy in the training set trades off with the increased execution time as the matching requires at least  $K - 1$  extra DTW computations as opposed to only 1 for a top-1 scheme. As we will show ahead, DTW computations incur heavy CPU budget on the wearable device.

In general, we observe from the results that the FAR can be decreased by increasing the music cue duration. We can observe (from Figures 8, 9 and 10) that the improvement is less significant when the music cue duration is increased from 5 sec to 6 sec, however, the improvement is more significant when the music cue duration is increased to 10 sec. In *Headbanger* the data collection phase for the authentication system (sampling accelerometer sensor readings) is executed in parallel with the music cue. The data processing phase involving the filtering, classification and matching is executed only at the end of the music cue and in the same order. We note that, the data input duration of 5-10 sec for authentication may seem long, but in reality, such data input durations are on par with those of password based systems [48].



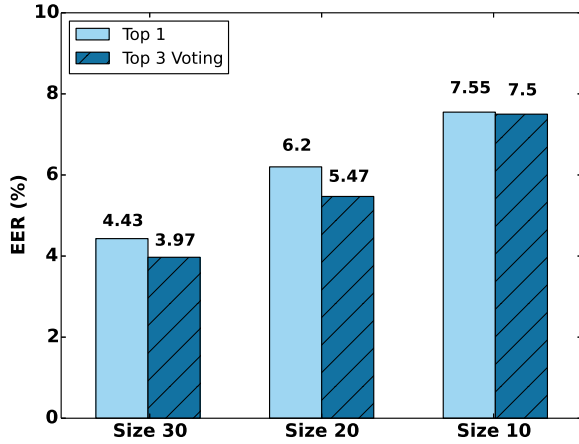


Fig. 14. Comparison of EER for different training sample sizes (30, 20 and 10) with fixed  $n$  value of 2.7

6) *Impact of Training Set Size:* Recalling from *Headbanger* section IV, the input to the training phase is a set of temporal signals (samples with duration equal to the music cue duration), each corresponding to one trial of the head-movements from the user. Our evaluations so far considered a training set size of 30 samples. In Figure 13, we report the EER in *Headbanger* for three different training data set sizes; 10, 20 and 30 samples. We can observe from Figure 13 that the EER holds an inverse relationship with the training set size. A larger training set minimizes the variance in mean and standard deviation computations, as the errors in their inconsistency are reduced by averaging the mean and standard deviation estimates over a larger set of data. On the other hand, a larger training set also implies a longer execution time of the training phase. However, in our system design, we posit that the training phase can be conducted offline on a more compute efficient device (smartphone, PC or server) and that the wearable device can pre-fetch the trained data (for example, an XML file), prior-to or during data collection phase, through a wireless link.

7) *Impact of Sampling Rate:* Due to DTW is resource-consuming, one direct way to reduce the workload of our algorithm is to decrease the sampling rate of the accelerometer and remain the sampling time. Based on NyquistShannon sampling theorem, since the high cut of our filter is 10 Hz, the minimum sampling rate should be 20 Hz. Also, the highest sampling rate and the default sampling rate of our platform are 200 Hz and 50 Hz accordingly. Thus, we choose these three value to evaluate the impact of sampling rate. In Figure 12, we observe that 200 Hz provides the best performance among three value, while 50 Hz and 20 Hz are giving closed results. The EER of 20 Hz is \*\*, comparing with \*\* of that of 200 Hz. Since the decrement of EER is insignificant and we can achieve 10 times speedup in DTW computing, 20 Hz will be a ideal value of system implementation.

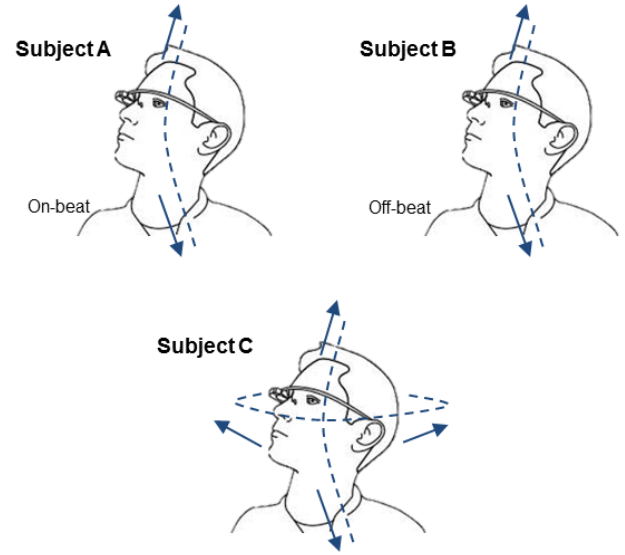


Fig. 15. Pictorial description of how the mimicked subjects move.

### B. Is it hard to imitate?

1) *Participants:* We had total of 38 volunteer participants. The participants list included a total of 32 males and 6 females. The average age of the participants was 25.6 years with a standard deviation of 6.6 years. The youngest participant was 22 years old while the eldest was at 49 years.

2) *Procedure:* Our second experiment aimed at an practical imitation attack field test scenario. In this experiment, three subjects were taken video while they were performing their successful login movement. Note that the music cue is usually played via a bone conduction speaker or a earplug, hence a camcorder is difficult to capture the music sound if the environment is noisy or the microphone is not sensitive enough. In this case, the imitators will be impossible to synchronize the music with the video. To eliminate this concern, we set the volume of the speaker to maximum and took the video in a quiet laboratory environment.

The participants were divided into three group, and each group was asked to imitated only one of the three users above. During the test, the participants could watch the video for as many time as their willing at anytime between two trials. A feedback from our system would be provided after each trail so that the participants could decide whether they needed to adjust their movement or not. After total number of trials reached 30 for each participant, the experiment would stop regardless the participant succeed or not. The investigator was not only recording the total number of successes, but also the number of trail before the first successful login. This experiment was conducted in quite space on campus. We will now discuss our evaluation results for both experiments in detail.

3) *Results:* Although it is difficult to quantitatively to describe the complexity of the movement in 5-Dimension space (3-axis accelerometer, time space, and response to the music beat), there are some distinguish characteristics of these three subjects, hence they are chosen to become our imitated

	Total Imitator	Successful Imitator Number	Average Number of Trial before First Successful Login	FAR (%)
Subject A	12	7	10.33	15.83
Subject B	13	3	14.33	2.77
Subject C	12	3	17.67	2.72
Overall	38	13	13.17	6.94

TABLE I. IMITATION ATTACK EXPERIMENT RESULT. SUCCESSFUL IMITATOR NUMBER REPRESENTS THE NUMBER OF THE IMITATORS THAT SUCCEED AT LEAST ONCE. AVERAGE NUMBER OF TRIAL BEFORE FIRST LOGIN INDICATES THE AVERAGE TIMES OF TRIAL A SUCCESSFUL IMITATOR TAKES BEFORE THE FIRST LOGIN.

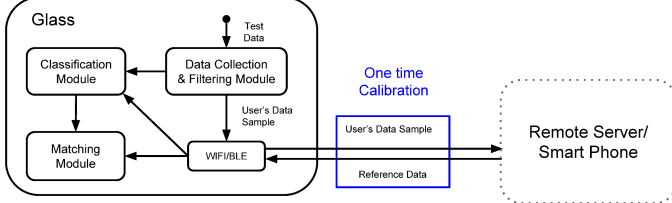


Fig. 16. Software modules of *Headbanger* implementation

subjects. As shown in Figure 14 *SubjectA* performed a simple nodding movement by naturally following the music flow. *SubjectB* also performed a simple nodding, but his movement was always off-beat with the music. *SubjectC* performed a movement combined with nodding and shaking, and he only nodded/shake at certain beats instead of every beat, which makes his movement is relatively difficult to learn. Table I shows the overall result of this experiment. The overall FAR is 7.54 %, while the individual FARs are 17.67%, 9.82% and 3.27% accordingly. Since *SubjectA* perform the simplest movement among these three subjects, 6 out 10 subjects could succeed at least once during their 30 trials, while for *SubjectB* and *SubjectC* this number is 3 of 15 and 3 of 10.

### C. Headbanger Google Glass App Implementation

We implemented *Headbanger* on Google glass, positioning it as an authentication application (app). Figure 15 shows the main software modules in the app. Upon initiation by the user, the app plays a music cue for a stipulated duration. The user conducts head-movements in synchrony with the music cue while the app records the accelerometer sensor in parallel. At the end of the music cue duration the app executes the data processing phase where the sensor readings are input to the *Headbanger's* software modules for processing. The processing stage includes the filtering of the accelerometer sensor values, classification and feature extraction using DTW, and threshold based matching of the generated features with those from training set. Upon completion of data processing, the app responds with a YES or NO textual output on the Google Glass screen, depending on match score.

In our current implementation, the training phase is conducted offline, prior to live-testing off the application. The training phase involves collecting 30 samples (variable) of

music cue duration (s)	response time (s)	time breakdown (%)		
		Filtering	DTW	Thresholding
10	1.93	0.50	99.50	<0.01
6	1.15	0.64	99.36	<0.01
5	0.88	0.81	99.19	<0.01

TABLE II. MEASURED RESPONSE TIME OF *Headbanger* APP IMPLEMENTATION ON GOOGLE GLASS WITH DIFFERENT MUSIC CUE DURATIONS AND FOR  $K = 1$ . THE RESPONSE TIME REPORTED HERE IS AN AVERAGE OVER 20 TRIALS.

the head-movement accelerometer readings, generating the features, and saving them into a local server (running on PC) as an XML file, with appropriate indexing. Upon app initiation on Glass, the trained features are pre-fetched from the server through a wireless connection. This ensures that the training set is readily available during the authentication process, thus eliminating the additional processing time required for the training phase. Conducting online training, particularly that involves DTW computations, is very compute intensive on a resource constrained devices such as Glass. One possible solution would be for the Glass to offload the training phase computation to a local server machine.

1) *Response time*: In Table II we report the measured average response-time of the *Headbanger* implementation on Google Glass app for music cue durations of 5,6 and 10 seconds. We conducted the benchmark execution-time profiling of *Headbanger* on Glass in a controlled indoor laboratory setting with no mobility. We define response time as the time elapsed between music cue completion to the display of authentication response (YES/NO text) on the Glass screen. Our measurements indicate that the response time is within 5 seconds for a 10 second data input, and is almost halved for a 5 second data input. We feel that a response time of 2-5 sec for a local authentication solution in Google Glass is comparable to that of prior-art that comes close to our solution [17], [48]. It is also important to note that authentication solutions that execute locally on head-worn wearable devices, especially on a heavily resource constrained device like Glass, are still not mature. However, the hope is that such solutions will possibly catch up to speed in the near future and that our approach is advancing one step in that direction. In Table II we also report the execution time of the key processes in *Headbanger*; filtering, DTW computation ( $K = 1$  requires 1 DTW computation), thresholding based similarity matching. We can observe from Table II that the DTW computation dramatically compute intensive than the other processes.

It is important to note that our current implementation uses a faster version of the DTW algorithm called Fast DTW [45], providing about 2x speed-up in DTW computation. We believe that the response time can be reduced further through strategic methods such as, further optimizations in the Fast DTW algorithm or pipelining the app execution along with data collection. A specific strategy for reducing response time for rejected attempts can be that, after a short duration, before the entire music cue is played, if it is found that a user's movement does not match the signature of the claimed user with a sufficient pre-determined confidence level, then the on-site classification may be terminated instead of waiting for the

Component	Power Consumption (mW)	Duration (s)
Sensor	29	10
Speaker	410	10
CPU	1600	14.4

TABLE III. POWER CONSUMPTION ON GOOGLE GLASS OF COMPONENTS RELEVANT TO *Headbanger*. THE CPU (RUNNING AT MAXIMUM FREQUENCY) POWER CONSUMPTION INCLUDES THAT OF THE HEADS-UP DISPLAY SCREEN BEING ON AS WELL. DURATION MARKS THE TIME FOR WHICH COMPONENT WAS ON DURING THE A 10 SEC MUSIC CUE LENGTH TRIAL

entire duration to yield the rejection. Another example, may include cyber-foraging strategies to offload heavy computation tasks, such as online training and classification, to the user's Bluetooth paired smartphone or a nearby cloudlet [25].

## V. DISCUSSION

In this study, we showed that head-movements have the potential to be used as a reliable behavioral signature for user authentication. We will now discuss some of the limitations that we identified from this work and prospects for future work as below.

### A. Power consumption

Google Glass is an example of a wearable device that is heavily battery power constrained. Measuring the power consumption of the Glass's battery is a challenging task as that requires physically dismantling the device. We refer to the measurement paper on Google Glass by Robert et. al [36] for the power consumption of the key components relevant to *Headbanger* implementation on Glass: the speaker for music cue playback, the accelerometer sensor and the CPU being ON during the entire authentication process. We report the relevant numbers in Table III. While the high CPU power consumption may not necessarily be surprising, the speakers also extrude considerable energy from the battery. We note that one possible solution for future consideration would be to play the music cue as intermittent notes over the duration, for example a ping or a beat sound periodically, where the speaker would be switched ON only during playback.

### B. Is this secure?

An authentication system must have an effective protocol ensuring security of the authenticating user's data. Our system runs an implicit authentication protocol where the user is given a finite set of (calibrated) music tracks to pick, based on which the user makes head-movements that are used as unique signatures for authentication. Our design assumes implicit security of the user's data, as a user voluntarily accepts the enforcement of conducting head-movements in response to the music. It is arguable that such enforcements are an integral part of most commonly used authentication systems; for example, typing a password, swiping the finger on the fingerprint sensor, approving of the camera recognizing the face. In all these cases the user is aware that he/she is inputting data into the system for authentication.

One way of compromising security would be a successful spoof of the head-movement by an adversary. For example, head-movements from an authorized user may be imitated by an adversary attempting to login to the device. If the head-movements from the user is regular (such as a nod), it may be easily imitated as opposed to a random head-shake such as a head-bang. To understand the effect of imitation on the accuracy of authenticating a user to *Headbanger*, we conducted an experiment (under the same set up as described in section V) where 29 volunteer participants were asked to imitate the head-nod movements of one user (one of the authors) who was trying to authenticate to the device using a 10 sec music cue. A total of 30 trials were conducted of which 10 samples were used as test data and 20 for training. Our evaluations of this dataset resulted in reasonable accuracy values of, an EER of 7.2% and a balanced accuracy  $BAC = 1 - ((FAR + FRR)/2)$  of 94.5% for the authorized user. Our results indicate that attacking the system through imitation of a simple head-gesture can still be challenging.

### C. Multi-Modality

Inconsistencies in the accelerometer sensor such as drift and temporal bias can significantly affect the nature of inferred head-movement signature. Head-movements, on the other hand, may also evolve over time for a person which call for periodic calibration of the system and/or the training data. The array of motion sensors (accelerometer, gyroscope, inertial measurement unit) open up opportunities for multi-modal motion sensing. For example, in Glass, accelerometer data can be combined with gyroscope measurements to provide multi-dimensional head-movement features that can improve the quality of the inferred signatures. Head movements can also be combined with other body movements to generate valuable, reliable signatures for authentication. For example, through a simple test experiment using the Google Glass infrared (IR) light sensor (we had to root the Google Glass to access the IR sensor unit) we observed that the blinking and winking patterns of users in response to the music stimulus were reasonably differentiable among users. Such patterns may also independently serve as another biometric that can be used for authentication purpose, or can be combined with head-movements for better results. Recent studies have shown that heart beat or pulse can also serve as reliable biometric for authentication purposes [3], [27]. We reserve such potential enhancements to our system for future implementation.

### D. Large Scale User Study

To be adopted as a primary authentication mechanism on smart-glass devices, the technique will have to be evaluated over a large number of usage and over a large user base. Conducting such rigorous large-scale experiments is typically infeasible in academic laboratory settings. We reserve such large scale experiments for future work, and hope to accomplish through industry collaborations. We will, however, be releasing our data-sets to the public in the near future.

## VI. RELATED WORK

Headbanger is an authentication system which focused on musical head movement.

Below, we review the related literature on mobile device authentication.

The work by Harwin et al. [26] is usually considered the first to propose use of head gestures by combining pointing and movements for human computer interaction. In [49], the authors used eye-blinking pattern as a unique feature for authentication. They achieved 82.02% accuracy with 9 participants. Compared to eye blinking pattern, head-movements can provide much more entropy, therefore can be considered as a more suitable biometric characteristic.

The work by Rogers et al. [43] proposes a approach that capturing user's unconscious blinking and head movement to identify a user from a group of users (20 users). They asked the users to view a long series(34 seconds) of rapidly changing picture with 10-second initiate phase. Our system only requires at most 10 seconds for the data collection phase, which is more practical for a real system.

The work by Ishimaru et al. [30] comes close to our system design; they proposed to combine the eye blinking frequency from the infrared proximity sensor and head motion patterns from accelerometer sensor on Google Glass to recognize activities (e.g., reading, talking, watching TV, math problem solving) The key difference of our approach from [30] is that, their approach focused on common head-movement and eye-blink patterns when people employ the same activities such as reading, typing, etc. We carefully investigated the head-movements from human subjects and found that they are unique to each person. Our system also identified these head-movements with a higher accuracy (95% versus 82% in [30]).

There are also a number of physiological activity recognition studies using computer vision [27], [35]. While [35] primarily uses computer vision to detect head gestures, BioGlass [27] combines Google Glass's accelerometers, gyroscope, and camera to extract physiological signals of the wearer such as pulse and respiratory rates. Camera processing on wearable devices, especially Google Glass is compute intensive and has a high energy budget [36].

Accelerometers have long been used to sense, detect and also recognize movements in other parts of the body; for example, gait recognition requires sensing in areas such as waist [6], pocket [23], arm [24], [40], leg [22] and ankle [21]. These techniques, though well known, may not be suitable for on wearable devices due to complexity (computation and energy) in the machine learning process.

Hand gesture and touchscreen dynamics are often coupled for authenticating to a (touchscreen) device. A number of contextual features including biometrics [44] (e.g. finger length, hand size, swipe/zoom speed, acceleration, click gap, contact size, pressure) and behavioral feature (e.g. touch location, swipe/zoom length, swipe/zoom curvature, time, duration) have been exploited as effective features for authentication purpose [11], [18], [20]. While most of the techniques require users to explicitly conduct a gesture following a specific pattern, TIPS [18] proposed a multi-stage filtering with dynamic

template adaptation strategy to perform the user authentication in uncontrolled environments – when a users naturally their phone.

There is indeed a significant prior art in authentication system implementations using various techniques such as speech [42], computer vision and image [10], graphical passwords [8], gestures [46], biometric fingerprints [31]. In this paper, we do acknowledge the viewpoint that our approach can also be used as a complementary scheme to most of the existing techniques in the authentication application space.

## VII. CONCLUDING REMARKS

We developed a system that uses head-movement patterns of users for direct authentication to a wearable device. We developed a light-weight approach that infers head-movements of users in response to music and generates signatures that are unique to every user. Our technique specifically uses the dynamic time-warping (DTW) tool to generate a head-movement feature that contains the mean and standard deviation of the DTW score of each user, determined over a multiple-user data set. The matching is conducted based on a thresholding scheme. Through a 30 user based experiment based evaluation using accelerometer traces collected using our data collection app on Google Glass, we observed that the average true-acceptance rate of our approach is at 95.1% and the false acceptance rates (FAR) at 3.9%. From our evaluation over 30 subjects' data we observed that a 10 sec and  $K = 3$  yield the least *EER* of 3.97%. We observed that the FAR can be reduced by increasing the music cue duration or by using more samples for feature extraction (use Top  $K$  samples) or by increasing the training data set. We implemented *Headbanger* on Google Glass and profiled the execution time of the key system modules and observed response time of about 4.47 sec for a 10 sec music cue duration and reduces to 2.44 sec for a 5 sec music cue duration. Our profiling indicated that the most compute intensive part of the app (of the order of few seconds) was the classifier that involved DTW computation. We believe that such high compute times can be reduced through optimized algorithms or through strategic techniques such as pipelining the data input and execution process. The multi-user data sets were validated and verified during the course of our evaluations and will be released for public use in near future.

## REFERENCES

- [1] Fitbit. <http://en.wikipedia.org/wiki/Fitbit>.
- [2] Google glass. [http://en.wikipedia.org/wiki/Google\\_Glass](http://en.wikipedia.org/wiki/Google_Glass).
- [3] Nymi band. <http://www.nymi.com/>.
- [4] Smart watch. <http://en.wikipedia.org/wiki/Smartwatch>.
- [5] H. J. Ailisto, M. Lindholm, J. Mantjarvi, E. Vildjiounaite, and S.-M. Makela. Identifying people from gait pattern with accelerometers. In *Defense and Security*. International Society for Optics and Photonics, 2005.
- [6] D. J. Berndt and J. Clifford. Using dynamic time warping to find patterns in time series. In *ACM KDD workshop*, 1994.
- [7] R. Biddle, S. Chiasson, and P. C. Van Oorschot. Graphical passwords: Learning from the first twelve years. *ACM Computing Surveys*, 2012.

- [8] C. Bo, L. Zhang, X.-Y. Li, Q. Huang, and Y. Wang. Silentsense: silent user identification via touch and movement behavioral biometrics. In *ACM MobiCom*, 2013.
- [9] K. W. Bowyer, K. Chang, and P. Flynn. A survey of approaches and challenges in 3d and multi-modal 3d+ 2d face recognition. *Computer vision and image understanding*, 2006.
- [10] Z. Cai, C. Shen, M. Wang, Y. Song, and J. Wang. Mobile authentication through touch-behavior features. In *Biometric Recognition*. Springer, 2013.
- [11] R. Challis and R. Kitney. The design of digital filters for biomedical signal processing part 3: The design of butterworth and chebychev filters. *Journal of biomedical engineering*, 1983.
- [12] E. F. Clarke. Rhythm and timing in music. *The psychology of music*, 2:473–500, 1999.
- [13] C. Cornelius, R. Peterson, J. Skinner, R. Halter, and D. Kotz. A wearable system that knows who wears it. In *ACM MobiSys*, 2014.
- [14] A. De Luca, A. Hang, F. Brudy, C. Lindner, and H. Hussmann. Touch me once and i know it's you!: implicit authentication based on touch screen patterns. In *ACM CHI*, 2012.
- [15] S. Egelman, S. Jain, R. S. Portnoff, K. Liao, S. Consolvo, and D. Wagner. Are you ready to lock? In *ACM CCS*, 2014.
- [16] T. Feng, J. Yang, Z. Yan, E. M. Tapia, and W. Shi. Tips: context-aware implicit user identification using touch screen in uncontrolled environments. In *ACM HotMobile*, 2014.
- [17] P. Fraisse. Rhythm and tempo. *The psychology of music*, 1:149–180, 1982.
- [18] M. Frank, R. Biedert, E. Ma, I. Martinovic, and D. Song. Touchalytics: On the applicability of touchscreen input as a behavioral biometric for continuous authentication. *IEEE Transactions on Information Forensics and Security*, 2013.
- [19] D. Gafurov, P. Bours, and E. Snekkenes. User authentication based on foot motion. *Signal, Image and Video Processing*, 2011.
- [20] D. Gafurov, K. Helkala, and T. Söndrol. Biometric gait authentication using accelerometer sensor. *Journal of computers*, 1(7):51–59, 2006.
- [21] D. Gafurov, E. Snekkenes, and P. Bours. Gait authentication and identification using wearable accelerometer sensor. In *IEEE AIAT*, 2007.
- [22] D. Gafurov and E. Snekkenes. Arm swing as a weak biometric for unobtrusive user authentication. In *IEEE IHHMSP*, 2008.
- [23] K. Ha, Z. Chen, W. Hu, W. Richter, P. Pillai, and M. Satyanarayanan. Towards wearable cognitive assistance. In *ACM MobiSys*, 2014.
- [24] W. Harwin and R. Jackson. Analysis of intentional head gestures to assist computer access by physically disabled people. *Journal of biomedical engineering*, 1990.
- [25] J. Hernandez, Y. Li, J. M. Rehg, and R. W. Picard. Bioglass: Physiological parameter estimation using a head-mounted wearable device. In *IEEE MobiHealth*, 2014.
- [26] R. Hoyle, R. Templeman, D. Anthony, D. Crandall, and A. Kapadia. Sensitive lifelogs: A privacy analysis of photos from wearable cameras. 2015.
- [27] R. Hoyle, R. Templeman, S. Armes, D. Anthony, D. Crandall, and A. Kapadia. Privacy behaviors of lifeloggers using wearable cameras. In *ACM UbiComp*, 2014.
- [28] S. Ishimaru, K. Kunze, K. Kise, J. Weppner, A. Dengel, P. Lukowicz, and A. Bulling. In the blink of an eye: combining head motion and eye blink frequency for activity recognition with google glass. In *ACM AH*, 2014.
- [29] A. K. Jain, L. Hong, S. Pankanti, and R. Bolle. An identity-authentication system using fingerprints. *Proceedings of the IEEE*, 1997.
- [30] A. K. Jain, A. Ross, and S. Prabhakar. An introduction to biometric recognition. *IEEE Transactions on Circuits and Systems for Video Technology*, 2004.
- [31] S. Jana, A. Narayanan, and V. Shmatikov. A scanner darkly: Protecting user privacy from perceptual applications. In *IEEE SP*, 2013.
- [32] Z. Jorgensen and T. Yu. On mouse dynamics as a behavioral biometric for authentication. In *ASIACCS*, 2011.
- [33] R. Kjeldsen. Head gestures for computer control. In *IEEE ICCV Workshop*, 2001.
- [34] R. LiKamWa, Z. Wang, A. Carroll, F. X. Lin, and L. Zhong. Draining our glass: An energy and heat characterization of google glass. In *ACM APSys*, 2014.
- [35] R. E. Milliman. Using background music to affect the behavior of supermarket shoppers. *The Journal of Marketing*, 1982.
- [36] F. Monrose and A. D. Rubin. Keystroke dynamics as a biometric for authentication. *Future Generation computer systems*, 2000.
- [37] F. Okumura, A. Kubota, Y. Hatori, K. Matsuo, M. Hashimoto, and A. Koike. A study on biometric authentication based on arm sweep action with acceleration sensor. In *IEEE ISPACS*, 2006.
- [38] T. Rahman, A. T. Adams, M. Zhang, E. Cherry, B. Zhou, H. Peng, and T. Choudhury. Bodybeat: a mobile system for sensing non-speech body sounds. In *ACM MobiSys*, 2014.
- [39] D. A. Reynolds, T. F. Quatieri, and R. B. Dunn. Speaker verification using adapted gaussian mixture models. *Digital signal processing*, 2000.
- [40] C. E. Rogers, A. W. Witt, A. D. Solomon, and K. K. Venkatasubramanian. An approach for user identification for head-mounted displays. In *Proceedings of the 2015 ACM International Symposium on Wearable Computers*, pages 143–146. ACM, 2015.
- [41] N. Sae-Bae, K. Ahmed, K. Isbister, and N. Memon. Biometric-rich gestures: a novel approach to authentication on multi-touch devices. In *ACM CHI*, 2012.
- [42] S. Salvador and P. Chan. Toward accurate dynamic time warping in linear time and space. *Intelligent Data Analysis*, 2007.
- [43] M. Sherman, G. Clark, Y. Yang, S. Sugrim, A. Modig, J. Lindqvist, A. Oulasvirta, and T. Roos. User-generated free-form gestures for authentication: Security and memorability. In *ACM MobiSys*, 2014.
- [44] S. V. Stevenage, M. S. Nixon, and K. Vince. Visual analysis of gait as a cue to identity. *Applied cognitive psychology*, 1999.
- [45] E. Von Zezschwitz, P. Dunphy, and A. De Luca. Patterns in the wild: a field study of the usability of pattern and pin-based authentication on mobile devices. In *ACM MobileHCI*, 2013.
- [46] T. Westeyn and T. Starner. Recognizing song-based blink patterns: Applications for restricted and universal access. In *IEEE FGR*, 2004.
- [47] J. O. Wobbrock. Tapsongs: tapping rhythm-based passwords on a single binary sensor. In *Proceedings of the 22nd annual ACM symposium on User interface software and technology*, pages 93–96. ACM, 2009.
- [48] M. Zentner and T. Eerola. Rhythmic engagement with music in infancy. *Proceedings of the National Academy of Sciences*, 2010.