Detection of mobile phone vibrations during walking

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Abstract

Today the use of mobile phones are widespread, and they are often kept in trouser pockets. As the thigh is comparatively less sensitive to vibrations, and vibrotactile sensitivity is diminished during movement, detection of vibratory mobile notifications during walking is lower than in a still position. Vibrotactile detection rate is hypothesized to be dependent on gait phase.

Method: 28 subjects were recruited to walk with a mobile phone in their pocket. Vibrations of random patterns were delivered during a two-minute session. Accelerometer data was recorded to analyze the gait pattern.

Results & Discussion: No phase-dependent effect was found. However, consistent with previous studies, a linear correlation between vibration duration and detection rate was found, but only up to durations of one second. Possible explanations are discussed.

1 Introduction

Today mobile phones are in everyday use by a vast majority of the western population. The increasing number of ways to communicate via for example email or instant messaging services have begun to move from being strictly computer-based to also be available in mobile phones, in addition to the already standard Short Message Service (SMS). As people depend more and more upon quick responses to mobile phone notifications, it might be less acceptable to miss messages, emails or phone calls. A mobile phone provides two primary ways of notifying its user; sound and vibration. These may work well in many situations. Sound provides the ability to notify the user even when the phone is not in direct or indirect contact with the skin, and vibration can be an effective and discrete way to get the attention of the user when sound notifications may be inappropriate or even inefficient, such as in noisy environments.

Many users keep their mobile phones in their trouser pockets (Karuei et al., 2011), where the phone is in indirect contact with the thigh. Due to this, many people seem to have trouble noticing mobile phone events when they are walking. This is consistent with the thigh being the one of the least sensitive areas for vibrotactile stimuli (Karuei et al., 2011) and in addition, the contact between the phone and the skin is hindered by the cloth of the pocket (Baek et al., 2006), which may dampen some of the vibrations. Of course, in addition to this, the movement of the leg while walking reduces vibrotactile sensitivity. Studies consistently confirm that cutaneous sensitivity for both vibrotactile and electric shocks is reduced when the tested body part is moving, or even when the muscles are activated (Post et al., 1994; Angel & Malenka, 1982; Karuei et al., 2011). The study by Karuei et al. (2011) shows in particular that the detection rate is diminished for vibrotactile stimuli to the thigh when walking.

The inhibitory influences on vibrotactile sensitivity are due to both peripheral feedback from the nervous system, and the motor commands from the brain (Post et al., 1994). An earlier suggestion that the “signal-to-noise” ratio is increased because of increasing noise during motor activity was concluded to not be a sufficient explanation (Post et al., 1994).

1.1 Vibrotactile sensitivity

In the human skin, different kinds of mechanoreceptors respond to touch and pressure in various ways. Vibrotactile detection is primarily handled by two types of cells, Meissner’s corpuscles and

Pacinian corpuscles (Goldstein, 2001). Considering vibrations from mobile phones, vibrations with frequencies of around 200 Hz (Yao et al., 2010) or 130-180 Hz (Baek et al., 2006), the most interesting mechanoreceptor is the Pacinian corpuscles, as their threshold is a U-shaped function of frequency, ranging from 40 Hz to 600 Hz, but having a minimum threshold at 250-300 Hz (Gescheider et al., 2004; Goldstein, 2001).

Pacinian corpuscles, as well as Meissner's corpuscles, are *rapidly-adapting receptors*, which means they respond to the onset and sometimes offset of a stimulus, but are not active during the stimulus (Goldstein, 2001). This explains why they are so effective in reacting to vibratory stimuli; they only react to changes in pressure, which is what vibrations consist of.

Although most vibrotactile research has examined the impact of frequency, the duration of vibrations is also studied to some extent. The Pacinian corpuscles exhibit a property called *temporal summation*, where the detection threshold decreases due to an increase in either vibratory duration or the number of stimuli in a sequence. This has been demonstrated for durations up to 1 second. (Gescheider et al., 2004; Goldstein, 2001)

There are two distinct mechanisms that have been suggested to be at work behind this phenomenon. First, according to Zwislocki's theory of *neural integration*, neural responses decay exponentially, reducing the activity in half every 200 milliseconds. When a vibratory stimulus is presented, activity

Because of this non-instant decay, activity can build up to reach a threshold level if new activity is being added fast enough. (Gescheider et al., 1999) Secondly, the mechanism of *probability summation* is simply the observation that the detection of stimuli is more likely the longer the stimuli is presented, i.e. longer vibration durations. Gescheider et al. (1999) concluded that for durations up to 800 ms, temporal summation can be explained by neural integration, but for durations over 800 ms, probability summation can account for the increased detection rates.

1.2 Purpose

Bussmann et al. (2000) investigated the signal of an accelerometer fixated on the thigh of six subjects during walking. The accelerometer data exhibited a consistent and characteristic pattern during each gait cycle. In particular, one large peak, named P_{12}, was found consistently one time each cycle. They found that gait analysis using a thigh-fixed accelerometer is feasible.

During a full step while walking, called a gait cycle, different muscles are active at different times (DeLisa & Kerrigan, 1998). Also, the varying positions of the leg should reasonably affect how the mobile phone is pressed against the thigh by the pocket, providing closer contact in some parts of the cycle. Therefore, it is reasonable to assume that sensitivity to the vibrotactile stimuli from the phone varies over the gait cycle, providing some optimal phase of the cycle to use for vibrations. We can thus predict the following:

Hypothesis 1 *There is a difference in detection rate for different phases of the gait cycle.*

As the Pacinian corpuscles have the capacity for temporal summation, we can also predict the following two hypotheses:

Hypothesis 2 *The detection rate will be positively correlated with vibration duration.*

Hypothesis 3 *The number of pulses should not influence detection rate*

The aim of this thesis is to provide a basis for making notifications in mobile phones more noticeable when the user is walking and carrying the phone in their pocket. This thesis will only study the effects of varying the pattern and timing of vibration, and not vibration strength, frequency or other mechanical properties, as these are not possible to vary using ordinary mobile phones.

1.3 Study

Since most modern phones today have a built-in accelerometer, it should be possible to detect the phase of the gait cycle and adapt vibrations to the current gait pattern of the user, thus making them more noticeable, provided that hypothesis 1 can be supported.

The present study will examine the effects of different vibration patterns on the detection rate of walking subjects. To resemble actual usage scenarios, vibrations will be delivered via a mobile phone placed in the subjects' trouser pockets. The vibration patterns will vary in length and number of pulses. Using this, this study aims to answer hypothesis 2 and 3. Also, accelerometer data will be recorded to enable analysis of hypothesis 1.

2 Method

An experiment was conducted to investigate the sensitivity for different vibration patterns during walking.

2.1 Materials

The same mobile phone, a Google Nexus One, was used for all trials. Attached to the phone was a simple headset with a button originally intended for answering calls. A custom software application was developed and used to vibrate the phone at given times and to record all accelerometer data, button presses and vibrations made.

2.1.1 Vibration frequency

To verify that the mobile phone used a frequency suitable for human perception, an audio recording was made of the phone when it vibrated against a hard surface. The microphone was also placed on this surface. The sampling rate of the audio recording was 44100 Hz. The waveform of the audio, which was a sinusoid wave, was then analyzed in an audio software (Audacity) and the number of wave tops during 100 milliseconds of vibration were counted as 22, giving a frequency of 220 Hz.

2.2 Procedure

28 subjects were asked to walk around indoors in a large hall in one of the university buildings. All subjects were students at Lund University and wore pants. While walking they had the mobile phone in one of their front pockets. The subjects were instructed to press the button on the headset when they felt the phone vibrate. The headset button was kept in their hand during the entire trial. Subjects were also told to walk as normal as possible.

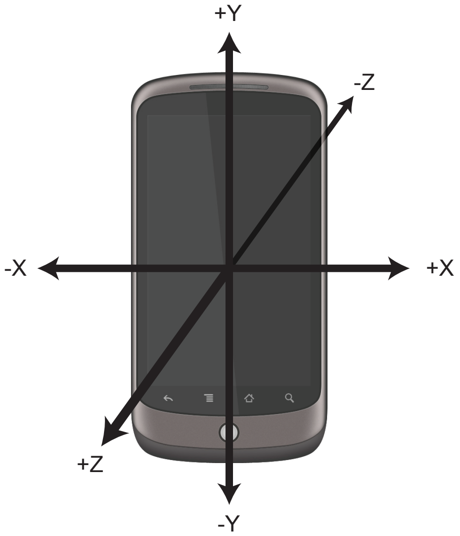


Figure 1: The phone used in the experiments with the different axes of the accelerometer

The first three subjects walked for five minutes, but as this was considered too long for most subjects, it was reduced to only two minutes for the remaining subjects.

The subjects were free to position the phone in whichever direction they wanted, and in any of their two front pockets. The reason for staying indoors was to ensure constant temperature, since there is evidence that vibrotactile sensitivity depends on temperature (Green, 1977).

2.2.1 Vibration patterns

The mobile phone vibrated every ten seconds in a random pattern. The duration of the entire pattern was between 100 and 2099 ms long, with each pattern divided evenly at random into between 1 and 7 segments. During segments 1, 3, 5, and 7 the vibration was on, while segments 2, 4, 6 were pauses where the vibration was off. This resulted in vibration patterns with between 1 and 4 pulses with pauses between pulses having the same duration as the pulses. By mistake, in two of the trials, the duration of the pattern was between 500 and 2499 ms long. Despite this, these trials were included in the study.

Because of the algorithm described above, the distribution of vibrations among different durations

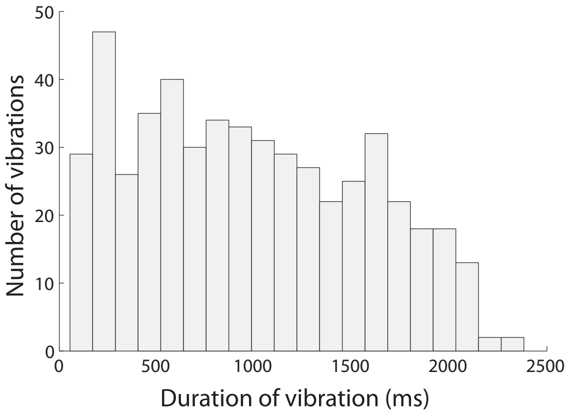


Figure 2: The distribution of vibrations delivered in the experiment

was not even. This is due to the fact that both a randomized pattern of one segment and one of two segments give rise to a vibration pattern with just one pulse, since the second segment is simply result in a pause. The actual distribution of vibrations is shown in figure 2. This was unintentional.

The motivation behind the chosen duration intervals was that 100 ms is somewhat longer than the minimum 50 ms recommended by Kaaresoja & Linjama (2005) and 2099 ms is almost the duration of two complete gait cycles (Bussmann et al., 2000; DeLisa & Kerrigan, 1998).

2.3 Data recording

The application was set to record accelerometer data as fast as the operating system allowed, which was 25 Hz. However, due to a programming mistake, only the three first trials were recorded at this frequency, and the other at the lowest frequency offered by the operating system, which was 5 Hz.

2.4 Data analysis

The recorded data consisted of three parts: (1) three-dimensional accelerometer data, (2) the time and duration of vibration patterns and (3) the time of button presses. A computer program was written to process this data. To simplify the analysis, only the Z-axis of the accelerometer data was used in the analysis software. Because of the way the phone was positioned in the pocket, the Z-axis was the axis with the most protruding acceleration pattern. Also, this enabled comparison with data presented in Bussmann et al. (2000).

For the phase-dependent analyses, 8 subjects were excluded. The reason was that their accelerometer data was too irregular to be analyzed be the software, which resulted in that the peaks were not consistently found.

2.4.1 Peaks – dips or tops

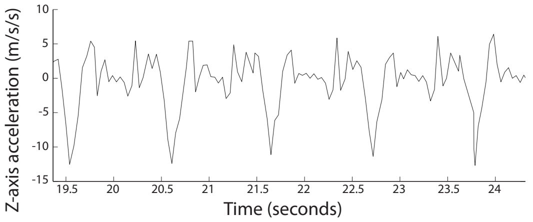
As can be seen in figure 3a and 3b there are evident peaks that are either downward (*dips*) or upward (*tops*) in the accelerometer data that correspond to high deceleration or acceleration in the Z axis of the phone (see figure 1). These peaks were assumed to match the P_{12} peak of Bussmann et al. (2000) and thus occur once in each step. Therefore they could be used to identify a consistent phase in each step.

To find these peaks, each trial first needed to be classified as either having tops or dips. Then a threshold value was used to "cut off" the data and thus effectively group data points that were considered to belong to the same dip or top. If the trial consisted of tops, the value of each data point needed to be larger than the threshold value to be included in a peak–group. And conversely, if the trial consisted of dips, the value needed to be lower than the threshold to be included. After this grouping, the maximum value for tops or minimum value for dips was located for each group. This value was then considered to be the actual top or dip. Figure 3c illustrates this process for data consisting of dips, using a threshold of $-5m/s^2$.

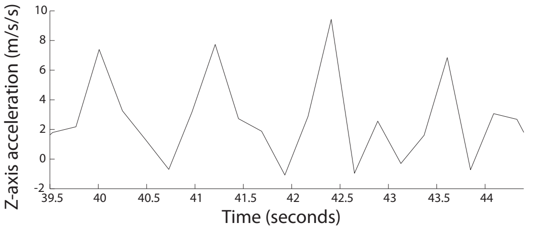
Both the classification of whether each trial consisted of tops or dips as well as a suitable treshold value was determined manually by looking at the data in MATLAB and adjusting the treshold value until the peaks were found satisfactory.

2.4.2 Potential delay of the vibration

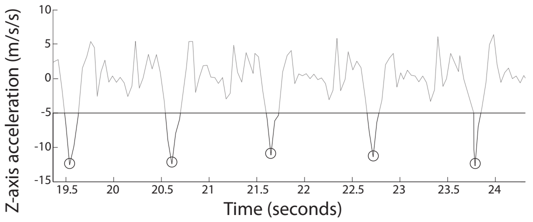
To be able to analyze the data, it was neccessary to investigate if there was any delay between the time when the application commanded the phone to vibrate and when the actual vibration started. A short experiment was conducted based on the assumption that updating information on the screen is nearly instantaneous. The application used in the experiments was modified to update the screen just



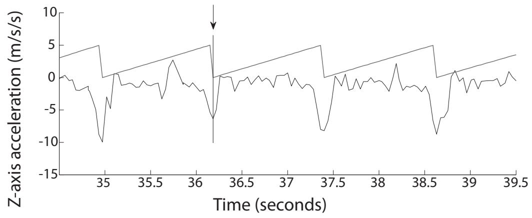
(a) dips when the phone's screen faces the leg. High-frequency recording



(b) tops when the phone's screen faces forward. Low-frequency recording



(c) Showing accelerometer data cutoff. Circles indicate found dips



(d) Accelerometer data with phase overlay. Notice how the phase returns to zero when the dip is found, as indicated by the arrow

Figure 3: Typical Z-axis accelerometer data used in the analysis

before the vibration command was executed. While running this experiment, the screen of the experiment phone was filmed. This enabled a simple qualitative video analysis of the recorded movie. It was found that the sound wave of the vibration started the frame after the screen had changed. This indicated that the vibration could at most be delayed by one frame, which in this case corresponded to $\frac{1}{30}$th of a second, or 33.3 milliseconds.

2.4.3 Phase detector

In order to see if there were differences between phases of the step cycle, an algorithm was developed to identify the phase of the step for a certain time point. To find the phase for a certain time, interpolation is made between the previous peak (0% of the cycle) and the next peak (100% of the cycle), so that the phase corresponds to the relative time within that interval. That is, the phase is calculated according to

$$phase(t) = \frac{t - t_0}{t_1 - t_0} \tag{1}$$

where t_0 is the time of the nearest peak before t and t_1 is the time of the nearest peak following t. The phase is usually expressed in percent.

Figure 3d shows accelerometer data with the phase overlaid. Note that the phase spans from 0 to 5 in the figure only for illustration. As can be seen, the phase increases linearly until a new peak is found and then returns to 0. The arrow and the vertical line indicate one such occurrence.

2.4.4 Verification of phase detector

The method described above of finding peaks and thus the phase of the step is novel and simplistic and has not been tested before. Therefore, it was important that the method was verified so that a calculated phase actually does correspond to the real phase of the step in a consistent manner. This was examined by filming one person (the author) walking on a sidewalk. The recorded movie shows the legs of the person. The movie and accelerometer data was synchronized by, while recording, holding the mobile phone in one hand and hitting it against the other hand quickly. This procedure gave rise to a short but strong peak in the accelerometer data so that it could be synchronized to the recorded movie.

The same phase-detection algorithm as described above was then used on the accelerometer data to generate a graph of the phase over time (similar to figure 3d). Following this, a qualitative analysis of how the movement of the leg correspond to both the accelerometer data, as well as the phase was performed. The purpose was two things. First, to see whether the phase was detected consistently between steps, so that any given phase corresponds to the same leg position in each step (reliability). Second, to examine which leg positions that correspond to different phases (external validity). This showed that in 20 subjects the spikes were found correctly once each step. But for the remaining 8 subjects the data was too irregular to analyze using the method described above.

3 Results

Of the 347 vibrations delivered to the 28 subjects, 132 (38%) were detected. The individual variation between subjects was large, with 8 subjects (29%) not detecting a single vibration, 8 subjects (29%) noticing less than half and 12 subjects (43%) subjects detecting more than half of their respective vibrations. For the 20 subjects (71% of the total) included for gait-dependent analysis, 237 vibrations (68% of the total) were delivered, 107 (46%) of which were detected.

In figure 4 the influence of vibration duration on detection rate is shown. A positive correlation between vibration duration and detection can be seen for all lines, except 4 pulses, up to about 1000 ms where the increase stops. A drop in detection from 56% (the top) to 40% (the dip) can be seen for vibrations between 1500 and 1750 ms. A more clear presentation can be seen in figure 5.

Considering the duration of the vibrations, the mean reaction time was fairly low; 1268 ms (SD = 525) from vibration onset. As can be seen in figure 6, the reaction time was not largely influenced by the duration of vibration in question. This is especially evident for the longer vibrations where more than half of the reactions were made before the vibration had ended.

The number of pulses in the vibration pattern did not seem to have any effect on the detection rate. Detection rates were 39%, 37%, 40% and 36% for vibrations with 1, 2, 3 and 4 pulses, respectively.

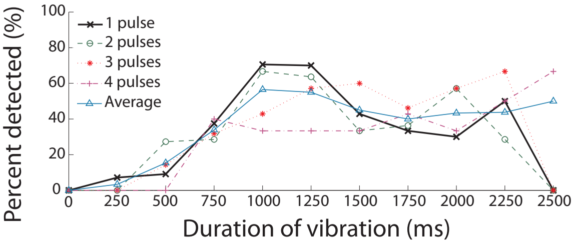


Figure 4: Detection of vibrations with different durations for 1,2,3 and 4 pulses. Durations have been grouped in to 250 ms intervals. Thus, 250 represents all durations between 250 and 499 ms

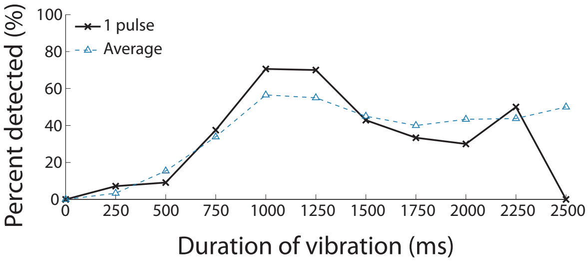


Figure 5: Only one-pulse vibrations and the average extracted from figure 4

The phase of the gait cycle did not influence the detection of vibrations. As figure 7 shows, even though there are small variations, the level of detection is overall constant.

The duration of the average step time for subjects varied between 1119 ms and 1888 ms having a median of 1506 ms. Thus, the median walking speed was 0.66 steps per second.

4 Discussion

The overall detection rate of 38% roughly matches the results of Karuei et al. (2011). As this detection rate is neither very low or very high, the vibrations made can likely be said to be near-threshold as required for comparison with Post et al. (1994).

This experiment demonstrates several characteristics of the detection of vibrations during walking.

4.1 Phase

Hypothesis 1 predicted that there should be a phase-dependent difference in detection rate. With

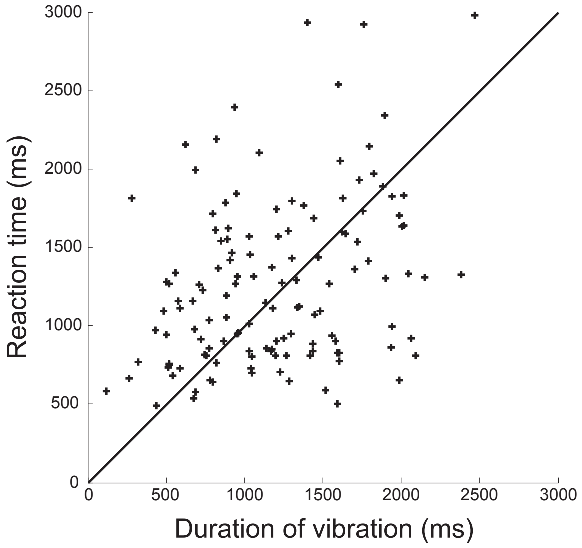


Figure 6: Plot of reaction times for vibrations with different durations. Each marker is a detected vibration. The straight line shows hypothetical reaction time if subjects would react instantly to the end of the vibration.

the results obtained in this study, this hypothesis can not be supported.

4.2 Pulses

Consistent with the prediction of hypothesis 3, no difference in detection rate could be seen for vibrations with different number of pulses.

4.3 Duration

Hypothesis 2 predicted that duration was going to contribute positively to the detection of vibrations. From figure 5, this is clearly the case for vibrations up to one second in duration. The apparent decrease for longer vibrations suggests that it is less effective to vibrate for 1700 ms than for 1000 ms. Neither the mechanisms behind temporal summation or neural adaption are suitable explanations for this phenomenon. The two mechanisms of temporal summation, neural integration and probability summation, has been suggested to have a pivot point at about 800 ms, which is within the range of the bar. But if probability summation would then be the contributing factor after 800 ms, the detection rate would still rise linearly since the duration is also increasing. Alternatively, one might propose that the Pacinian channel or higher levels of the central nervous system would adapt or habituate to the ongoing vibratory stimulus. This is certainly possible, although then the detection rate in the graph would be constant after 1000 ms which is clearly not the case, for single-pulse vibrations, as can be seen in figure 5. Another explanation is that there are higher-level mechanisms that react to changes in vibration but only within a certain interval of time. Such a system could work so that it activates at vibration onset and then decay exponentially, almost reaching its resting level when vibration offset would trigger activity again and the integration of both activation curves would be higher than a certain detection threshold, thus waking the subjects attention. If the duration between vibration onset and offset becomes too long, the activity has decayed fully and the second activity spike is not enough to reach the threshold. Such a hypothetical system would explain the decrease in detection rate after a certain duration, but would also have the side effect that the number of pulses in the vibration should have an effect of detection rate. Since this is not the case, this explanation is not sufficient either.

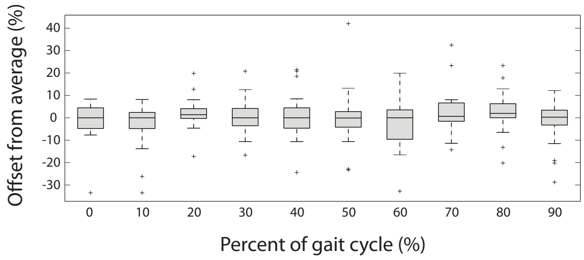


Figure 7: Detection of vibrations made in different phases of the gait cycle. Values represent the deviation from the average of each respective trial

The result becomes even more interesting when one considers the reaction times. For many of the long vibrations, subjects responded before the vibration had ended. When this happens, the duration of the vibration that is left can of course not influence the detection rate since the button has already been pressed. Up until the button press, the vibration is exactly the same regardless what happens afterwards. Therefore, the duration effect discussed above

However, this phenomenon should simply give rise to a constant detection rate above the duration

Reaction times were somewhat higher than reported by Karuei et al. (2011), but subjects in the current study were not instructed to react as soon as possible and thus may not be motivated to respond rapidly.

This implies that the influence of the duration on detection rate is much less than other factors, at least when the duration is longer than 1250 ms.

4.4 Methodological considerations

4.4.1 Accelerometer data

The accelerometer data measured in the high-frequency recordings is very similar in to that of Bussmann et al. (2000). The large P_{12} peak is especially evident, which was also used for detection of the phase. This corroborates the validity of using the accelerometer of a phone for gait analysis.

4.4.2 Recording frequency

The low recording frequency of the accelerometer data does introduce a larger uncertainty in the detection of peaks and thus an error in the calculation of the phase. However, the P_{12} peak is still clearly evident in the low-frequency data. The low recording frequency of about 5 Hz means that there is an uncertainty of 200 ms for the time of the peaks. The width of one bar in figure 7 corresponds to roughly 150 ms (10% of the median step time). Thus the uncertainty is larger than the accuracy of the figure. This means that there could theoretically be a phase-dependent effect working on a shorter time-scale.

4.4.3 Distractions

Since the subjects' only task was to respond to detected vibrations to one certain body site, the thigh, one can theorize that they would be more susceptible to detecting the vibrations than in actual usage where they would not know when a vibration was coming. But from the study made by Karuei et al. (2011), expectation does not seem to contribute much to the detection rate. One other source of potential enhancement of detection rate is that subjects might have responded to the sound producted by the vibration. Even though no subject reported any such observation, it can not be excluded that it might have affected the results. Kaaresoja & Linjama (2005) and Post et al. (1994) had subjects listen to pink and white noise, respectively, in headphones to filter out the sound of vibrations.

4.4.4 Frequency of vibrations

The mini-experiment described in section 2.1.1 showed that the vibration frequency of the phone was 220 Hz which is close to the frequency range around 250 Hz that the Pacinian corpuscles are most sensitive for (Goldstein, 2001). Since the sampling rate of the audio was 44100 Hz, there should be no risk of so called frequency folding (Weeks, 2007), and although possible, it is unlikely that the recorded frequency results from resonance. Thus, the mobile phone vibrated at a frequency suitable for human detection.

4.4.5 Delay verifier

Since the largest possible delay of 33 ms is much lower than the error margin of the recorded accelerometer data (around 200 ms in the worst case), this delay is considered to be negligable.

4.4.6 Phase verifier

Consistent with Bussmann et al. (2000), this analysis showed that for 20 subjects, events such as *heel strike* occurred right after a peak, the peak being when the leg is most stretched out just before touching down on the ground. The phase verification experiment also showed that the method used was not sufficient to recognize the spikes in the data.

5 Future work

As the duration effect discussed earlier is very interesting, a new experiment could be performed, aiming purely at identifying this phenomenon. If there is shown to be a inhibitory effect of longer vibrations, it is indeed a novel result that this study is not able to provide a satisfactory explanation for.

Further studies could investigate the phase-dependency in greater detail and with higher recording frequency. For example, more parameters could be controlled for, such as gait speed, clothing, body type and cognitive work load. Also, the method used for finding spikes and thus the phase of the gait cycle should preferably be developed further.

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