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Vibrational Analysis on Patellofemoral Joint Degradation of Swine's Knee

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Abstract. Knee’s severe patellofemoral joint degeneration gives a lot of people difficulty to endure daily life because walking or any leg movement can cause serious pain. At present, physical examination, x-ray and MRI are often used to diagnose the condition; however, each of the methods has its own disadvantages. For instance, physical examination is highly dependent on the skill of the doctor who practiced the examination, which cannot avoid misdiagnosing the condition. X-ray can detect wounds and tears, but the accuracy is also not top-notch since the result of an x-ray is a 2-dimension picture. MRI is the most reliable method for diagnosing the condition; however, the cost is very high. We propose that other than x-ray and MRI, patellofemoral joint degeneration can be identified by analyzing vibrational signals obtained from an accelerometer attached to the patella while sitting and moving the leg up and down. At the beginning of the study, swine’s knees are used to imitate human’s knee. Swine’s knees with various surface degradation levels are put on a machine that mimics the mechanism of knee motion. An accelerometer is mounted on the patella of the swine’s knee while the machine is running to measure the friction and roughness induced vibration of the patella. The vibration results suggest that more surface degradation the higher vibration signal amplitude. Nevertheless, the method still needs a lot more improvement on the database and testing procedures, in order to make it accurate, dependable and affordable. Hence, with further analysis on patient’s knees it is highly possible to determine whether patient’s knee is degraded or not and at what degradation level.

1. Introduction
Knees are one of the most important anatomies in our human body, they helps the walking, running, and jumping movements possible, while also supporting the entire body’s weight. There are four main parts, which comprise a knee: femur, patella, tibia, and fibula. From long and endured usage of knees, they can become degraded, makes it painful to move, this can happens to anyone, however, athletics are more prone to this problem due to the overuse of the knees. Some develops Chondromalacia Patella (cartilage under the knee is softened) and some develops Osteoarthritis (wear and tear on the knee joints) just from walking. The degradation of knee is divided into 5 levels (or grades): 0 = healthy, 1 = minor spur growth/minor swell, 2 = greater spur growth/ knee density > 50%, 3 = obvious damage between...
cartilages and bone/ knee density < 50%, 4 = cartilage is fully degraded [1-2]. Patient’s knee degradation level can be confirmed by the use of MRI (Magnetic Resonance Imaging) [2-5], however, due to the expensiveness of the test, diagnosing the degradation of knees is very uncertain. Although, nowadays orthopedic doctors are able to detect the degradation by listening to the noise generated from the friction between the degraded knees [2-3], the accuracy of the test is only if the condition of the patient is beyond level 2 already, which at the time, might be too late to treat without undergoing a surgery. In addition, many people tend to wait until the problems presented and interrupted their daily life before checking for their health, this included their knees. Due to many reasons, such as, not considering that knees are working hard under the load applied by the users daily, or the diagnosis methods are costly, and if no problems presented, there is no need for them to check on them. If diagnosed before the knees entered pain-stage, pre-cautious and prevention for the further degradation due to lifestyle will be able to slow the inevitable degradation of the knees, thus create opportunity for patients to longer their knees’ lifetime.

Knee degradation and especially the patellofemoral joint degradation is researched in clinical features of symptomatic patellofemoral joint osteoarthritis by Peat G et.al. [6], where the research includes statistics and data from real gathered samples of the plausible causes of knee degradation and the symptoms of such injuries. In addition, the study by Cannon A et.al. [7] studied and explained about how the patellofemoral resurfacing arthroplasty, which is the most common method to cure the injury.

Three main diagnosis methods are normally practiced nowadays. The first is a traditional physical examination, where a doctor, expertise with knees, will do a simple knee bending and stretching examination and observe the motion. This method is highly dependent on the doctor giving the examinations. Although it is the easiest and cheapest method, it is the most inaccurate method among the three. The second method is the x-ray, which is inaccurate due to its two dimensions result. Third is the MRI which is very accurate, but it is very expensive. Many researchers [8-10] suggest the methods of acquiring signals to diagnose the knee degradation whereas the signals are obtained from a large sample size. The patients, whom the hospital has already received the permission, are asked to sit on a rigid table in a relaxed position with the legs hanging on the air, then a miniature accelerometer is attached to the middle position of the patella. In another literature by Cai S et.al. [8], the method is also used, and they obtained data that have high accuracy of 88-93%.

Patellofemoral cartilage is the white and smooth articulating surface of the patella and femoral trochlea of the knee joint. Loading to the cartilage usually consists of both compression and shear. Compressive stress on the patella comes from contraction of quadriceps and patella tendon during knee flexion. Shear stress comes from the translational motion between the patella and femoral trochlea as the knee joint moves. Mechanical damage due to wear could alter the friction of the articular surface, causing vibration. In this study, friction-induced vibration from friction change of the articular surface is characterized in terms of progressive articular cartilage deterioration.

2. Swine Knee Joint: Experiment
We studied the vibration signals from the knee swine model where the patellofemoral joints of the pig are dissected and separated from the swine leg. The swine’s knees are selected due to its similarity with human knees and their availability in many fresh meat markets. In our experiment, the swine’s femur and patella are first cleaned by scraping off the meat on the bones. Four levels of femur’s cartilage deterioration are then produced by means of mechanical rubbing from sandpaper so that its cartilage is thinning at the different levels until the bone is exposed. The femurs are rubbed 20, 40, 70, and 100 times with a constant force (figure 1a). As shown in figure 1b, a femur is tightly wrapped by elastic bands over our custom-made knee joint testing machine where the motion of knees is speed controlled. Then the patella is drilled at 5 locations, on the top for mounting the sensor using 4-mm drill, and 4 more on the sides of the patella for the screw mountings. After that, the side drills are screwed and hooked to the knee joint testing machine by dental elastic bands. Then the knee joint testing machine’s motor driver is connected to the voltage power supply via wires and the computer via a USB cable. The vibration signals are then taken from each level of cartilage damage using the accelerometer attached
on the patella, as the patella is translational moving at a constant speed. For each condition (no rub, 20, 40, 70 and 100 rubs), three sets of data are collected. Raw data from the measurement instrument is taken from the measurement instruments software in form of a text file and then converted into time-acceleration graphs. The filtering is then used, to minimize the residue occurred from noises. In this research’s filtering method is adapted from Cai S et al. [11], where the finite impulse response (FIR) filter, a common filtering method, is used. The method used temporal statistics which are averaged to obtain the output data at various point of time. The paper suggests that cascade moving average filter is implemented. The method combines the two successive-placed moving average operators. The band power is calculated from the short time Fourier transform. Because VAG (vibroacoustic) signal obtained from the experiments are aperiodic and non-stationary, i.e. it contains varying frequencies that do not appear throughout the whole data. The power $P_{f_1 f_2} = \int_{f_1}^{f_2} S_x(f) df$ is used to calculated for the average power in signal $x(n)$, in range $f_1$ to $f_2$, where $S_x(f)$ is the power spectral density (PSD) and the unit of $P_{f_1 f_2}$ is Watt.

![Figure 1. a) Using sandpaper to create wound b) swine knee subject setup.](image)

![Figure 2. Experiment setup for swine knee data gathering.](image)
3. Swine Knee Joint Testing: Results and Discussions

The shape of time-acceleration graph of no defect condition (figure 3a) is a distorted bell shape with spikes present along the curve. However, if we use the baseline wander filtered method, the graph (figure 3c) became a band with the present of spikes. The roughness of the bone and the vibration from the knee-motion machine could be the reason for the spikes shown on the curve. However, there are only a small amount of spikes on the curve which imply that the surface of patellofemoral compartments are quite smooth (figure 3b). Moreover, from the time-frequency graph (figure 3d), the intensity of the graph is not that high. The calculated band powers are, also, pretty low (see table 1). Therefore, we could say that the vibration produced from our knee-motion machine is quite low and the patellofemoral surface is quite smooth.

It can be observed that the amplitude and the number of spikes of the time-acceleration graphs of the swine knee after being rubbed by sandpaper 20, 40, 70, and 100 times (shown in figures 4a/c and 5a/c, for 40 and 100 rubs respectively) increase as the number of rubs increases. Hence, we can conclude that the smoothness of the time-acceleration graph depends on the condition of the swine knee. The amplitude and the spikes on the graph increase as the surface roughness increases as we rub more against the swine knee surface. For the time-frequency graph, we can see that the intensity of the graph seems to increase as the surface roughness increases so does the calculated band power.

![Figure 3. Swine knee with no defect: (a) Time [s]-acceleration [g] graph; (b) Femur surface; (c) Time [s]-acceleration [g] graph after baseline wander removed; (d) Time [s]-frequency [kHz] graph.](image-url)
Figure 4. Swine knee rubbed by sandpaper 40 times: (a) Time [s]-acceleration [g] graph; (b) Femur surface; (c) Time [s]-acceleration [g] graph with baseline wander removed; (d) Time [s]-frequency [kHz] graph.

According to the calculated band powers shown in table 1, we can see that the trend of the calculated power spectral density of the signal vertically normal to the movement direction for each frequency range is proportional to the number of rubs as we create more cartilage damage. Especially, higher power spectral density is observed at the high frequency components (500-1,000 Hz) as the level of cartilage damage is progressing.

It is noted that there are many types of knee injury, such as tear, wear, effusion, disruption and etc., and each type of the injury generates different kinds of signal patterns, much more research and data collecting must be done in order for our findings to be applied and usable with real patients. Our further research would be done on real patients. Their patella’s vibration signals will be collected, analyzed, and then verified with the MRI results. It is promising that, with some more studies, our proposed approach of using patella’s vibration signals to determine the degradation levels of patient’s knee would yield reliable and accurate outcomes.
Figure 5. Swine knee after being rubbed by sandpaper 100 times: (a) Time [s]-acceleration [g] graph; (b) Femur surface (bone exposed); (c) Time [s]-acceleration [g] graph with baseline wander removed; (d) Time [s]-frequency [kHz] graph.

Table 1. Overall band power for sandpaper degraded swine knee experiment.

| Frequency range   | $P_1$ (0 - 500 Hz) | $P_2$ (500 - 1000 Hz) | $P_3$ (200 - 500 Hz) |
|-------------------|--------------------|-----------------------|----------------------|
| No defect         | 1.6814 W           | 0.8436 W              | 0.5537 W             |
| 20 times rubbed   | 2.5074 W           | 1.0652 W              | 0.3709 W             |
| 40 times rubbed   | 5.3856 W           | 2.6031 W              | 1.5299 W             |
| 70 times rubbed   | 6.0100 W           | 3.7656 W              | 1.7610 W             |
| 100 times rubbed  | 5.5685 W           | 3.8564 W              | 1.8173 W             |
4. Conclusion
In order to raise awareness for healthy lifestyle of one’s knee before pain, a low-cost and effective method is needed. This study illustrated the potential use of the vibration signal for non-invasive detection of cartilage degeneration. An accelerometer is used to measure the vibration signals created by friction and surface roughness of the patella and femur of a swine knee. The signals are then analyzed to determine the severity of cartilage degradation. It can be seen that as the number of rubs on the cartilage increases the acceleration signals have more spikes as well as higher amplitudes. The vibration signal power in the frequency range of 0 to 1000 Hz also goes up as the cartilage becomes more damage. These results are quite promising with further research on human knees. That is we believe that the method of using accelerometer to measure vibration signals of the knee joint is worth the investment for some more studies to successfully implement on real patients.

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