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Machine Learning based Musculoskeletal Ergonomic Analysis of Knee Joint with Support Brace

Mythili C [1], *Ponram P* [2]

[1]*Assistant Professor, Department of Electrical and Electronics Engineering, University College of Engineering, Konam, Nagercoil, Kanyakumari District, Tamil Nadu, India.*

[2]*Research Scholar & Project Associate (DST SEED SYST Project), Department of Electrical and Electronics Engineering, University College of Engineering, Konam, Nagercoil, Kanyakumari District, Tamil Nadu, India.*

Email: mythilicdr@gmail.com

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Abstract

Musculoskeletal issues ranges from pains to mobility issues. Timely diagnosis of musculoskeletal disorders are important in prevention and treatment. Analysis of ergonomics of consumer durables fitting to human are always a complex task associated with time consuming and laborious work. In this present work, a machine learning based ergonomic analysis on knee with external support brace was carried out to understand the user comport of basic postures among a reference healthy and affected population. The study involves 3D scanning of knee joint of study population grouped in to different age groups and each group containing both healthy reference and population with prevalence of knee joint issues. The disease prevalence was categorized into low, medium and extreme cases based on the severity of mobility issues diagnosed. Duration of present in a particular posture is also recorded. Piezoelectric based pressure measurements carried out at important pressure contacts of the user. The data were feed in to MATLAB machine learning tool to train the system, after obtaining optimum training outcome testing and validation were performed to obtain the performance characteristics in terms of ergonomic comfort. The proposed system was able to classify between different comfort levels and may be evaluated with larger dataset for further clinical usage.

1. Introduction

The knee joint is one of the most complex and important joints in the human body. It is responsible for supporting the body's weight and allowing for movement, but it is also susceptible to a range of injuries and conditions that can cause pain and limit mobility (Pottie et al.). Some common knee joint Musculoskeletal issues are Knee Osteoarthritis, ligament injuries, Meniscus tears and Patellofemoral Pain Syndrome (Zaffagnini et al. Van Den, Bogert, et al. Winters, Stark, et al.).

Knee Osteoarthritis is a degenerative joint disease that occurs when the cartilage in the knee joint begins to wear down. This can lead to pain, stiffness, and swelling in the knee, as well as a decreased range of motion. It is more common in older adults, but can also occur in younger people who have had knee injuries or surgeries (Kubıcek, Z Florian, et al. Lippross et al. Kraan et al.).

Knee Ligament Injuries are injuries happens to the four main ligaments that help to stabilize the joint and prevent it from moving. These ligaments can be sprained or torn due to sudden twisting or impact, such as during sports activities or accidents. Symptoms of knee ligament injuries can include pain, swelling, instability in the joint, and difficulty bearing weight on the affected leg (Arnett et al. Childs et al.).

Meniscus Tears occurs in the two C-shaped pieces of cartilage called menisci, which act as shock absorbers and help to distribute weight evenly across the joint. These can become torn due to sudden twisting or repetitive use, such as in athletes who play sports that require pivoting or cutting movements. Symptoms of a meniscus tear can include pain, swelling, stiffness, and a clicking or locking sensation in the knee (Norkus, Floyd, et al. Hughston et al.).

Patellofemoral pain syndrome (PFPS) is a condition that occurs when the patella (kneecap) rubs against the femur (thigh bone) in a way that causes pain and inflammation. It is often associated with overuse, such as in athletes who participate in activities that involve repetitive bending of the knee. Symptoms of PFPS can include pain or aching in the front of the knee, especially when bending or squatting, swelling, and a grinding or popping sensation in the knee (Wascher et al.).

Treatment options for most of the knee musculoskeletal disorders may include RICE, physical therapy, pain management medication, and in severe cases, surgery is performed (Ferretti et al. Laprade et al. Hassebrock et al.).

Kamran Shamaei et al. (2013) proposed that the spring-like behavior of the knee joint led to the hypothesis that an external spring acting in parallel with the knee joint might partially replace the knee joint contribution during stance. They investigated the validity of this hypothesis using a pair of experimental robotic knee exoskeletons. Their findings are summarized as follows: ”In this study, they found that a spring in parallel with the knee joint can help unload the knee joint during the stance phase. They also found that the knee joint can accommodate a parallel spring with a wide range of stiffness up to ~80% of the natural knee quasi-stiffness, after which the parallel spring still provides assistance but the knee complex stiffness increases above the knee quasi-stiffness (Irmischer et al.).

Jiun-YihKuan, et al, described the design of a new knee joint mechanism, called the Adaptive Coupling Joint (ACJ). The new mechanism has an adaptive trajectory of the center of rotations (COR) that automatically matches those of the attached biological joint. Conventional exoskeleton and assistive devices usually consider limb joints as a one to three degrees of freedom (DOFs) joint synthesized by multiple one-DOF hinge joints in a single plane. However, the biological joints are complex and usually rotate with respect to a changing COR. As a result, the mismatch between limb joint motion and mechanical interface motion can lead to forces that cause undesired ligament and muscle length changes and internal mechanical changes. These undesired changes contribute to discomfort, as well as to the slippage and sluggish interaction between humans and devices. They showed that the ACJ can transmit planetary torques from either active or passive devices to the limbs without altering the normal biological joint motion (Harner, Höher, et al.).

Bingquan Shen, et al (2013), developed a wearable lower extremity assistive device intended to aid stroke patient during rehabilitation. The device specifically aims to assist the patient in sit-to-stand, stand-to-sit, and level-walking tasks in order to promote active gait rehabilitation exercises. The device adopts an anthropomorphic structure with hip and knee joint actuated in sagittal plane. A finite state machine strategy was proposed to control the device. At different states, appropriate assist torque is added to each joint. EMG signals are used to assess the assist performance. The development includes the design of the device's mechanical and electronic hardware. The device can potentially be used to assist stroke patient in similar tasks (Shea et al.).

Chen-Yu Cheng1, et al (2020), described that Low back pain (LBP) is a serious occupational disease. A main contributing factor to LBP is a burden on the lumbar region, which can occur when lifting heavy objects. To reduce the risk of LBP, squat-lifting, which uses knee torque, is recommended as a preferred alternative to stoop-lifting, which uses hip and back muscles. However, people tend to avoid squat-lifting due to its relatively low metabolic efficiency, and the greater force it places on the knee and rectus femoris. A knee assistive device prototype was fabricated that is easy-to-wear and light-weight, using shape-memory-alloy (SMA) wires that are inherently passive elements. This device consists of a commercial knee supporter and two strands of SMA wires. One device is worn on each knee. The SMA wires do not lose their elasticity even when they are bent at larger angles and generate restoring forces (Clayton and Court-Brown).

Jinfu Li, et al (2016), conducted the first experimental trial to offer gait assistance based on gait period functionality. The goal of this controller is to assist the gait of the impaired persons in order to reduce the walking efforts in their daily living. The performance of this approach is investigated on a single-leg lower extremity assistive device with a group of healthy subjects walking on a treadmill. Joint kinematics, assistive torques from assisted trial, and heart rates from all trials are recorded. Preliminary evaluation showed that this approach is capable of providing functional task gait assistance at hip and knee joint of the subject under varying walking speeds during level walking (Boden et al.).

From the study of existing works, it is understood that, although substantial work done on the musculoskeletal related brace support systems. There are limited studies only available to understand their performance in terms of mobility and ergonomic comfort. The present work analyses the user ergonomic comfort with machine learning models.

2. Materials and Methods

A Knee by-passing brace was designed to be used for elderly and obese persons for knee load distribution. The brace is intended to prevent knee joint disorders such as overlap and joint pains for aged and obese peoples. The top view is given in Figure 1 and the front view is represented in Figure 2. Knee joint disorders prevalent in aged persons which is due to wear of knee joints and overlap due to aging. This will cause mobility disorders and knee joint problem such as severe pain. By reducing the net load over knee joints, by an external load by-passing apparatus across knee joints, the overlap of joints will be reduced. This will ultimately prevents elders from undergoing knee replacement surgeries and getting immobility disorders.

Other than preventive care, this brace will also be a supportive mechanism for knees of aged persons who have knee joint issues. The design is validated for ergonomic compatibility with computer simulations. Validation and analysis of load distribution efficiency through computer simulation also done with MATLAB R2022 and FreeBody software applications.

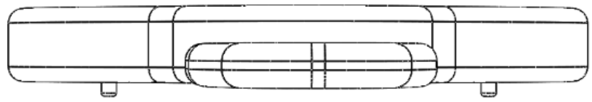

FIGURE 1. Top View of Support Brace

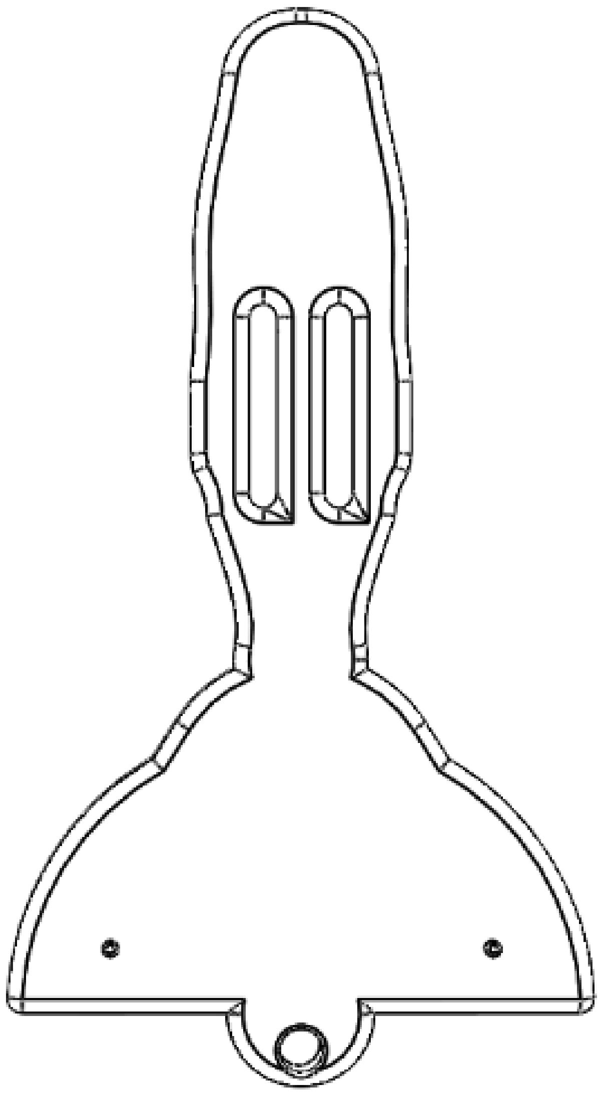

FIGURE 2. Front View of Brace diagram (300 dpi)

MATLAB software used in the work provides a variety of tools and functions for machine learning classification, including decision trees, support vector machines, and neural networks. The d to build accurate and efficient classification models for a wide range of applications, from image recognition to sentiment analysis. FreeBody software is a MATLAB extension app which provides knee joint simulation models (Cleather and Bull C. Daniel, Bull, et al. J. C. Daniel, Goodwin, and Bull J and Bull).

The Support Vector Machine (SVM) algorithm based classifier is used in this work to build image recognition and data based posture comfort classification. The SVM algorithm constructs a hyperplane or a set of hyperplanes that can be used for classification. The hyperplane is chosen to maximize the margin between the classes, which is the distance between the hyperplane and the closest points in each class. The SVM equation is represented as follows

$$minimize \ \parallel w \parallel^2 + C\Sigma\xi i \tag{1}$$

$$subject\ to\ yi\,(wTxi\ +\ b) \geq\ 1\ -\ \xi i \tag{2}$$

$$where\ \xi i\ \geq\ 0 \tag{3}$$

In the equation (1) where w is the weight vector, b is the bias term, xi is the input data, in equation (2) yi is the corresponding label, ξi is the slack variable, and C is the regularization parameter. The objective of the SVM algorithm is to minimize the norm of the weight vector (——w——ˆ2), where equation (2) & (3) represents the conditions, while ensuring that the data points are correctly classified and the margin is maximized.

The analysis was done after recording the pressure at three points namely P1, P2 and P3 along with knee angle deviation from the original posture angle named as Alpha angle comprising the four predictors and 118 observation of data were recorded.

The validation used in this study was 5-fold cross-validation and 13 numbers of observations were ear marked as test data were used for test analysis. The Linear Support Vector Machine based classifier was used.

3. Results and Discussion

The obtained overall accuracy in this study was 95.76% during the validation done with 118 observations with 4 predictors and the number of response classes were 3 namely low, medium and extreme comfort levels.

The obtained prediction speed on a i-7 Intel Core Processor machine with GTX 1080 Graphics processor is around 4800 obs/seconds and the net training time is 1.3002 seconds.

The confusion plot for the three classifications namely extreme, low and medium categories were reported for true and predictions in Figure 3. The True positive prediction for extreme category is 38 and false negative is 2 cases and false positive is 3 cases. 39 is the true positive classification for low category and there were no false positive and false negative predictions. 36 is the true positive detection for medium cases and false negative cases are 3 and false positive cases are 2. The kappa score obtained for this confusion plot is 0.936 and overall accuracy is 95.76%.

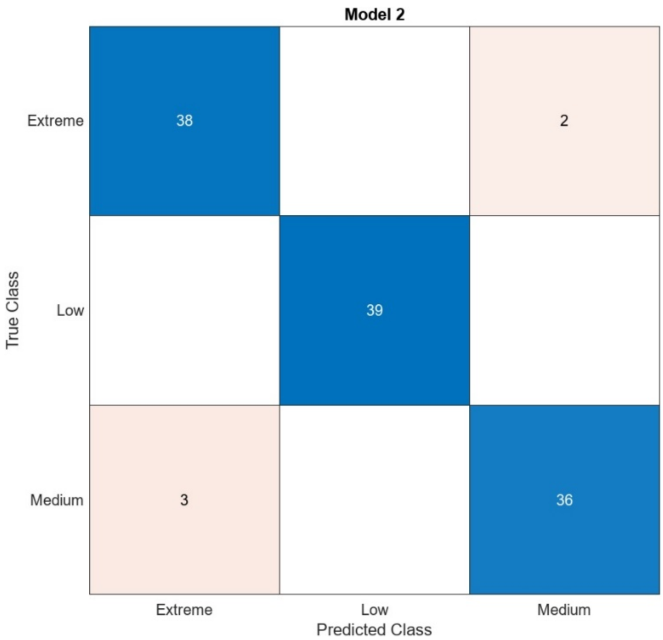

FIGURE 3. Confusion plot analysis

The sensitivity is 92.683%,100% and 94,737% for extreme, low and medium ergonomic comfort categories respectively The precision obtained is 95% for extreme, 100% for low and 92.308% for medium categories.

The figure 4 provides the receiver operating curve characteristics for the classification done which is remarkably above the standard limits. The area under curve for extreme is 0.9958, low is 1 and for medium is 0.9955. These results were in agreement with the study of Kumar et al 2021, in which they have evaluated the performance of a machine

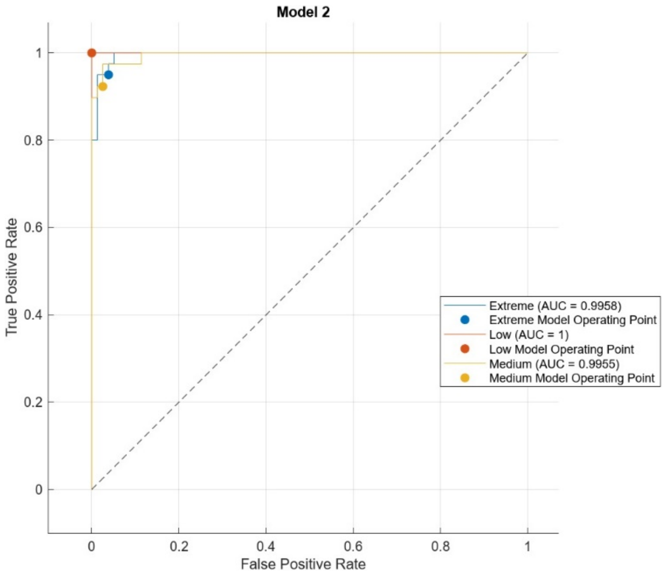

FIGURE 4. Receiver Operator Curve

learning-based classifier for the diagnosis of musculoskeletal disorders using X-ray images.

4. Conclusion

These results indicate that the classifier has excellent discriminatory power and can effectively differentiate between different types of ergonomic comfort levels of knee joint with knee braces. The findings of this study have important implications for the diagnosis and management of musculoskeletal disorders, and highlight the potential of machine learning-based approaches for improving clinical decision-making.

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6. Authors' Note

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the pa-per was free of plagiarism.

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