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KneTex – Improvements to a textile-integrated sensor system for feedback-supported rehabilitation after ACL surgery

Abstract: After surgery of the anterior cruciate ligament (ACL), unpredictable effects can occur in the patient's gait patterns. Thus, patients often experience instability and uncontrolled buckling of the knee joint ("giving way" effect). The "giving way" effect is also difficult to measure due to the uncontrolled and rare occurrence. Within the KneTex project a smart textile-integrated sensor and actuator bandage system is developed to detect instability of the knee joint and actively support the rehabilitation process. Based on the sensor data the calculation of the knee angles as well as a recognition system is implemented. The bandage system can be controlled via a custom app which is developed as part of the project. This paper describes the recent developments and current status of the project. In addition, the results and steps for future work are described as well.

Keywords: KneTex, IMUs, motion detection, giving way, cruciate ligament rupture, knee angle, recognition system, feedback system

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1 Introduction

The measurement of knee angles and related movements is subject of various research projects. Examples include effects on the performance of professional athletes [1] or the screening and prevention [2] of knee problems due to muscle weakness or knee joint surgery. There are several approaches that consider the field of care and the healing process after anterior cruciate ligament (ACL) reconstruction [3].

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The project KneTex [4] focuses on a mobile and easy-to-use bandage system, which can support the rehabilitation process in everyday use. For this purpose, the knee angle, flexion/extension, rotation and abduction/adduction, and the prevailing movement situation are measured, and the user is warned in the event of incorrect position by means of vibration actuation.

2 System overview

As already described in [5], the KneTex system includes, a bandage equipped with sensors and vibration actuators, an application for a smartphone (Figure 1: top right), a server (Figure 1: bottom centred) and a "standard" IT system, e.g., stationary PC or notebook (Figure 1: top left). The device records the user's movement data, forwards it to the server via WLAN and sends a signal to the user via the vibration actuators in case of incorrect movements. The server receives the data from each user, processes and stores it in a database. The stored data can then be viewed by the user and authorized physiotherapists/doctors via the KneTex website [6] on an IT device.

In the following, the improvements in comparison to [5] are presented and discussed. The focus is on the general

Figure 1: KneTex - system overview

use of the system, the used hardware components, the optimizations in angle calculation and the status of the classification system.

2.1 Device operation

To use the device, the bandages must be connected to a specially developed application on a mobile device via Bluetooth. For this purpose, it is necessary to log into the application using a corresponding account which can be created on the KneTex website [6]. Then the bandages can be connected to the mobile device in order to gain access to the various functions of the application. Functions include start/stop recordings, select labels during the training of the classification system (section 2.4) that describes the movement type during a recording (Figure 2a), send notifications to the server in case of an unusual event in the motion sequence like a giving-way, display battery status of the system (Figure 2 top), test actuators and upload sensor data to the server (Figure 2b).

The received sensor data on the mobile device are sent encrypted via the Internet (WLAN, mobile network) to the server, where they are stored and processed according to the user (Figure 1, bottom). This data can be viewed by the users via the KneTex website [6] and provides the ability to track and monitor their own movements. Furthermore, the users can authorize their healthcare provider (HCP) from a list of registered physiotherapists/doctors to permit read access. The authorization can be withdrawn at any time in the same way.

Figure 2: KneTex application, recording (a), upload (b)

Authorized HCP can view and evaluate their patients' data via the KneTex website, create findings and training plans and pass on the exercise plans directly to the patient.

2.2 Hardware structure

In this section the hardware structure and the arrangement of the sensors of the bandage system are described in detail.

The prototype bandage consists of two 9-DoF IMU sensors (ICM-20948), one atmospheric sensor (BME280) which allows the measurement of humidity, barometric pressure and ambient temperature, one 12-Bit analog to digital converter (ADS1015), a resistive bending sensor (developed by the Department of Textile and Clothing Technology at Hochschule Niederrhein as part of the project) and a micro-SD card module (No. 1 in Fig. 3a) to save the sensor data locally on a micro-SD card.

These components are used to obtain various parameters from the user. The parameters are used for the calculation of knee angles, for classification of the movement, and for the detection of the “giving way” effect.

For the modular construction of the bandage system and the connection of all components with the microcontroller (No. 2 in Fig. 3a), a circuit board has been

Figure 3: KneTex circuit board (a) and Overview of a prototype bandage (b)

developed as shown in Figure 3a. The modules are connected via I2C to the microcontroller and can be extended by adding new sensor nodes (No. 4 in Fig. 3a). In addition, the circuit board is also connected to the vibration actuators (No. 3 in Fig. 3a).

An external battery monitor (LC709203F, ON Semi-Conductor) is used to measure the State of Charge (SoC) of the lithium polymer battery. Compared to the ADC of the microcontroller ESP32, the battery monitor provides a higher accuracy (± 7 instead of ± 60 mV), at a consumption of $3\mu\text{A}$ (No. 5 in Fig. 3a).

The IMUs are positioned on the outside of the thigh and in the middle of the lower leg (No. 3 and 4 in Fig. 3b). The resistive bending sensor is integrated in the middle of the textile. A schematic illustration of the resistive bending sensor is shown in Figure 3b, No. 6. The atmospheric sensor is placed at the bottom of the textile (No. 2 in Fig. 3b). Furthermore, the battery pack on the back side is connected to the microcontroller board to supply all the hardware components (No. 5 in Fig. 3b).

2.3 Measurement of knee angles

After the sensors have been integrated as described in 2.2, the knee joint angles (flexion/extension, rotation, abduction/adduction) can be determined based on the IMU data. After further investigation of the previously used calculation described in the last paper [5], it was noticed that the system had accuracy limitations in certain leg positions. For this reason, the method of [7] was adapted for the present work. This resulted in the implementation shown in Figure 4.

Figure 4: Angle calculation process, adapted from [7]

Unlike before, the procedure does not use the magnetometer data. Nevertheless, to obtain valid angular results, all sensors must be aligned with the person's leg before a recording session could start. As the calibration values may differ depending on the person, the procedure must be repeated for each use. To determine the calibration factors the method from [8] was used. Thereby the person assumes an N-pose for ten seconds while the legs are fully extended. The acquired data can then be used to align the sensors vertically with the gravity vector. In this way, for example, the flexion/extension is set to zero degrees with legs fully extended.

As before, the accuracy of the angle results was checked using a motion capture (MoCap) system (camera based Qualisys system). Due to the adjustments, the angle calculation was optimized in different positions, improving the three angles. The addition of calibration eliminated offsets in flexion/extension, as well as in rotation by correcting the alignment of the sensors to the natural body shape. Compared to the camera based reference system, the KneTex system has an average standard deviation in flexion/extension of 2.54 degrees, in rotation of 2.43 degrees, in abduction/adduction of 0.96 degrees for squats and 1.95 degrees (flexion/extension), 1.5 degrees (rotation) and 2.7 degrees (abduction/adduction) for walking.

For illustration, the angular curves over time of flexion/extension (Figure 6, top), rotation (Figure 6,

middle) and abduction/adduction (Figure 6, bottom) during squats are shown. First, a short calibration is performed in the first 22 seconds (Figure 6, blue area) before starting the activity. The curves of flexion/extension of the presented system almost reach the deflections of the reference system. In contrast, the curves of rotation and abduction/adduction generally show the same course as the reference but are less pronounced. This difference could be caused by worse results of the reference system. With the reference, it should be noted that even the slightest shifting, reattaching, or covering of markers no longer leads to valid results, as the markers would have to be placed in the same position as when the system was calibrated. However, since attempts are also made to derive very small angles, this may only be possible to a limited extent with the reference. For this reason, it is planned to use an alternative MoCap system.

2.4 Classification system

A recognition system based on a random forest classifier is developed as part of the project to classify movement types. An overview of the classification system is shown in Figure 5. The classifier can be trained by pre-labeled sensor data, which is generated by the app during recording. Using a sliding window of one second width the system extracts 570 different statistical features (e.g., mean, minimum, maximum, standard deviation, interquartile range) from the raw sensor data and creates a number of decision trees.

After training, the model can be saved for further use.

Figure 5: Overview of the classification system

The trained model can be loaded with raw sensor data for one second and calculate the statistical features of the data to classifier movement patterns.

Due to the high number of training and test data and the differences in movement patterns, an average accuracy of 97,9% for the classes “walking”, “sitting”, “standing” and “stairs up” is obtained. The class “stairs down” has the worst accuracy with only 83,3% (Table 1). This may be explained by being the class with the least amount of data (Table 1). Hence, further investigations are currently being carried out for this class.

Figure 6: The angular curves of flexion/extension, rotation, and abduction/adduction

Table 1: Implemented classes and the accuracies

Class	walking	sitting	standing	stairs up	stairs down
training data/ min.	311,5	63	162,3	27,1	4
test data/ min.	4,7	9,6	8,4	0,55	0,1
Accuracies	99,3%	99,8%	98,6%	93,9%	83,3%

3 Conclusion and outlook

In the presented paper, an overview of the status of the KneTex project was provided. The hardware and software components as well as the arrangement of the sensors and actuators were described. Improvements of the angle calculation were achieved by adapting the general calculation approach and by adding an additional calibration of the sensors. Furthermore, the recognition system allows the classification of the movement patterns “walking”, “sitting”, “standing” and “stairs up/down”.

Further steps will address investigations on the feedback actuators to control the actuators in case of incorrect posture is detected. To increase usability, the circuit board and the sensor modules will be designed with flexible printed circuit board (PCBs) and integrated into the bandage system. Furthermore, the classifier and the calculation of the knee angles will be implemented on a smartphone to monitor movement patterns and to provide feedback during movement in real time.

Author Statement

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