Julia Demmer*, Andreas Kitzig, Nana Schlage, Gudrun Stockmanns and Edwin Naroska

Knetex – Development of a textile-integrated sensor system for feedback-supported rehabilitation after surgery of the anterior cruciate ligament

Abstract: Patients often report an effect after surgery of the anterior cruciate ligament which is called "giving way". This manifest itself by a drop of the knee or a felt instability. This phenomenon is difficult to measure and validate because it usually does not occur regularly and is not reproducible under laboratory conditions. The Knetex project takes up this point by trying to actively support the rehabilitation process with a bandage that can be worn in everyday life and is constructed as a smart textile using sensors and actuators. For this purpose, on the one hand it is attempted to actively record the phenomenon of the "giving way" by measuring knee angles etc. and by active user feedback. At the same time, the patient is specifically advised by means of actuators to correct incorrect posture or movement in order to make the rehabilitation process more effective and prevent further damage. Two 9-axis IMUs (inertial measurement units) form the basis of the system. These are used together with a textile strain sensor to calculate the knee angles. This paper gives an overview of the planned system, the initial experiments to measure the knee angles and the first results of the actuator study.

Keywords: cruciate ligament rupture, IMUs, smart textiles, motion detection, giving way, Knetex

https://doi.org/10.1515/cdbme-2020-3095

1 Introduction

In the field of knee angle measurement, systems already exist for research and commercial applications with different focus settings. The authors of [1] present a knee bandage that can measure two of three knee joint angles in real time, the angle of flexion and extension as well as the abduction/adduction angle. These were measured with textile strain sensors that have been integrated into the bandage. The system allows slow as well as very fast movements to be measured without artefacts and recorded with high accuracy of 0.5 degrees.

Another system [2] uses inertial sensors to measure the angles between selected body segments. The system has an accuracy of +/-1 degree in the sagittal and frontal plane and +/-2 degree in the transverse plane.

However, the presented systems also have restrictions. For example, there is often a limitation to one knee joint angle or only single points are focused, such as the sole calculation of angles or the determination of activity. Furthermore, the systems do not allow active feedback to support the user.

In this paper the concept of a smart bandage which is currently being developed in the project “Knetex” [3] is discussed.

The system focuses on a smart bandage that determines the angular extent of three different knee joint angles and the respective activity of the wearer with help of portable sensors. Furthermore, the bandage has selected actuators that are intended to draw the user’s attention to malpositions, especially the giving-way phenomenon [4]. The overall system is presented below.

2 System overview

In the "Knetex" project, a sensor-based textile aid is being developed to help patients with surgically treated anterior cruciate ligament ruptures in rehabilitation, as well as in everyday life and sports, to avoid incorrect posture and incorrect strain. In particular, the aim is to avoid the re-rupture and complication rates of the operated leg, as well as injury to the cruciate ligament of the healthy leg. The actuator system integrated in a bandage provides local and direct proprioceptive feedback by means of targeted, actuator-

***Corresponding author: Julia Demmer:** Hochschule Niederrhein, Reinarzstr. 49, Krefeld, Deutschland, e-mail: julia.demmer@hs-niederrhein.de
A. Kitzig, N. Schlage, G. Stockmanns, E. Naroska: Hochschule Niederrhein, Reinarzstr. 49, Krefeld, Deutschland

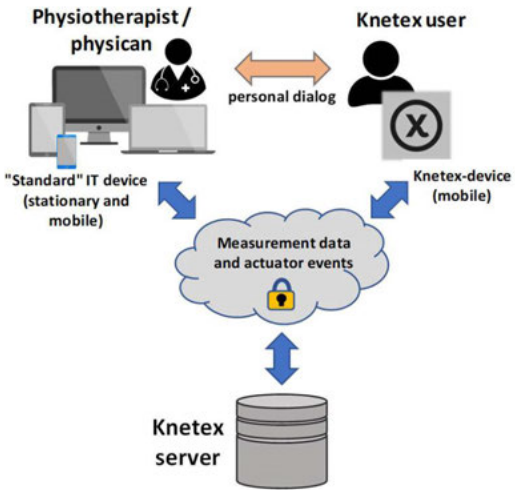

Figure 1: Knetex system Overview

implied stimuli as soon as unfavorable movement patterns are detected. The movement behaviour of a patient should be changed sustainably by repeated feedback during everyday activities and therapeutic exercises.

The initial system is shown in Figure 1. The key point is the Knetex device (in Figure 1: top right) that currently consists of a textile carrier in the form of a bandage in which sensors and actuators are integrated to detect the movements and angles of the user's knee and to notify the user in case of incorrect movements. The data is transmitted in encrypted form via the mobile network to a server (in Figure 1: bottom, centred), where it can be stored and prepared for the physiotherapist or physician (in Figure 1: top left). The processed data can then be displayed and evaluated using a standard IT system (stationary PC, notebook, mobile phone, etc.) in order to give the user feedback on the success of his treatment and to be able to adjust the therapy accordingly.

In the context of the present publication, the Knetex System will be presented and discussed in the following. The publication focuses on the presentation of the initial work on the design of the bandage with sensors and actuators and on the processing of the data for the calculation of the knee angles.

2.1 The Knetex device

The Knetex device shown in Figure 2 consists of two components. These are on the one hand the bandage with sensors and actuators and on the other hand a mobile device in the form of a mobile phone to acquire the data of the bandage, to control the actuators and to exchange the data with the Knetex Server.

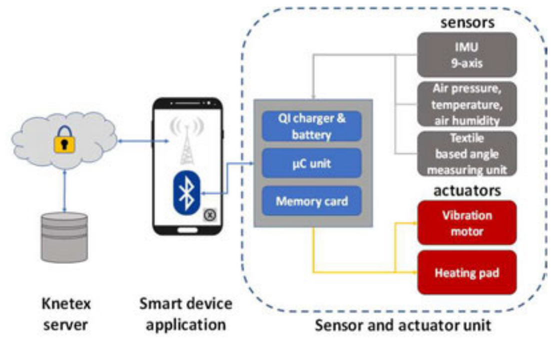

Figure 2: Block diagram of the sensor and actuator system

The sensors used in the current setup are two IMUs of type TDK ICM-20948 (9 DOF including an acceleration sensor, a gyroscope and a magnetometer), a combination sensor for measuring temperature, humidity and air pressure (Bosch BME 280) as well as an own design of a resistive bending sensor on a silicon carrier. A vibrotactile stimulator (coin type vibration motor of type B1034.FL45-00-015) as well as an own design of a thermal stimulator (resistance heating element) are used as actuators.

The control of the actuators and the reading of the sensor data is done by a microcontroller board based on an ESP32 microcontroller, the sensor data is buffered on a standard micro SD memory card for debugging purposes. The power supply is realized by a standard rechargeable cell phone battery which can be charged by an inductive charging circuit according to QI standard.

As data connection between mobile phone and microcontroller a wireless connection via Bluetooth is established.

2.2 Measurement of knee angles

To measure three different knee joint angles (flexion/extension, internal/external rotation, varus/valgus), the IMU data is used initially. In subsequent work, the resistive bending sensor is added to determine the knee angle and the barometric sensor data in combination with the IMU data are used later to determine the movement context.

Figure 3 shows the basic arrangement of the two IMUs (marked red) on the right knee. One sensor is attached to the outside of the upper leg, the other sensor is attached to the lower leg centrally below the knee. The white "globes" at both knees are passive markers of the reference measuring system and have no influence or function in the Knetex system.

The correctness of the knee angles determined with the help of the IMUs is checked by a motion capturing (MoCap) system (camera-based Qualisys system). This systems are often used as applications in biosignal processing, e.g. for gait analysis [5] or motion strategy analysis [6] and is used in this work as a reference system.

To calculate the three different knee joint angles the proposed method of [7] is adapted for the present work. The procedure of the implemented system can be described as followed:

1. Calculation of calibration parameters (offset, scale factor) for each sensor
2. Measuring 3D acceleration, angular velocity and earth vectors of both sensors
3. Calibration of the measured data of each earth magnetism vector
4. Calculation of two quaternions [8] between both acceleration vectors and the earth magnetism vectors
5. Estimation of a rotation matrix of each quaternion

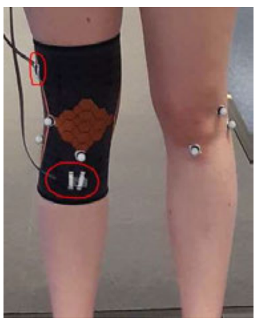

Figure 3: Attachment points of IMUs at the knee

6. Calculation of knee joint angles from the obtained rotation matrices

Steps two to six are iterated while measuring the three knee joint angles to enable a measurement in real time.

To minimize sensor errors while measuring knee joint angles calibration parameters must be calculated first. This includes the hard and soft iron corrections for the magnetometers. The parameters can be stored on the SD card so that they do not have to be recalculated each time the system is started. In order to guarantee a permanently reliable measurement, the calibration values must be checked and, if necessary, adjusted in a specified time interval. To continuously calibrate the measured sensor data during recording, an offset is subtracted from the sensor data of the respective sample value.

2.3 Knetex actuator system

In the following, the actuators used in the bandage are considered. The selection of the actuators was initially made by a preliminary examination of different actuator systems. As possible actuator mechanisms, nociception, thermoreception, acoustic stimuli and mechanical stimuli were examined for a possible application.

These were analysed for several factors, such as suitability in everyday life, security risks and corresponding measures and their dimensioning. Mechanical stimuli by means of a vibration motor as a vibrotactile stimulator and thermal reception, which is carried out as a thermal stimulator by means of a heating pad, have proven to be optimally suited for use on the knee.

The two actuator elements are driven in parallel by the microcontroller. Both systems are controlled by means of a PWM (pulse width modulation) to control the heating power and the motor speed. The heating pad is controlled in such a way that no higher temperature than 40°C is applied to the skin of the person using the system. Accordingly, the speed of the heating process up to the maximum temperature is the only parameter that can be selected. The vibration motors are controlled in such a way that a sinusoidal course of the vibration pattern is applied. Amplitude and frequency are selectable and frequencies in the range of 50 to 100 Hz were chosen for tests among the values reported in [9].

3 Evaluation and results

After the description of the Knetex system, the results of the first investigations on knee angle measurement and the acceptance of the actuator systems are presented below.

To test the accuracy of the angle calculation results, four subjects were asked to repeat two activities three times. The required activities were "Walking a defined route" and "Simulation of climbing stairs". The respective resolution of the individual sensors used is: ±2g for the acceleration sensor, ±250°/s for the gyroscope, ±4900µT for the magnetometer.

The first results for "walking" and "climbing stairs" show on average very small deviations of the Knetex system compared to the MoCap reference system (2,40465 degree and 6,17735 degree). The standard deviation for the two activities in degree are 9,1958 and 4,7399.

The two actuator systems in the form of the vibrotactile and the thermal stimulator were evaluated in a separate test series with 11 test persons. For this purpose, both systems were attached to the knee one after the other in a bandage. The test persons had to complete a task in the form of the "nine hole peg test" [10] and simultaneously signal by means of a switch when they noticed the stimulation of the respective system. The time between activation of the stimulation and the test person's recognition of the stimulation was measured and resulted in the reaction time. The resulting response times were on average 3,19s and 0,28s standard deviation for vibrotactile stimulation and on average 103,96s and 55,81s standard deviation for thermal stimulation. The results show that vibration as an actuator was recognized faster, better and more clearly than the thermal stimulation which took a few seconds to reach its maximum temperature of 40° and was often not even noticed. For this reason, thermal stimulation was classified as unusable so that vibrotactile stimulation will be used in the following set ups.

4 Conclusion and outlook

In the context of this work the project Knetex was presented and an insight into the initial work to create the system was given. Furthermore, it was shown how the "Smart Knee Bandage" as a complete system with sensor and actuator technology as well as the connection for the supervising physiotherapists is currently being realized in the Knetex project. First, the knee angle measurement using the IMUs was presented. The results currently still show deviations. Reasons for the relatively strong deviations can be explained on the one hand due to slipping of the bandage (a universal bandage was used which was not suitable for every person) and on the other hand due to errors in the reference measurement caused by not optimal positioning of the markers. The results show that there is room for improvement, but it could be also shown that the initial system is already able to derive suitable knee angles. In a further initial test, it was also possible to show on a test person that a "giving-way" can be detected in the data. For a study the accuracy of the system has to be improved, because the effect of a giving way in the sensor signals is relatively small. The second point that was presented was the actuator technology used. Here it could be shown that a vibrotactile stimulus is preferable to a thermal stimulus. Overall, it could be proved that the approach works and can be used for a bandage functionalized by means of sensors and actuators. This approach will be further developed and equipped with additional sensors and methods of biosignal processing and will be extended to the overall system presented at the beginning of this publication.

Author Statement

This project was funded by the European Regional Development Fund (EFRE-0801285). Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. The actuator study was approved by the Ethics Council of the German Sport University Cologne (No. 116/2019). The authors would like to thank their project partners from the companies Bache Innovative (Torsten Bache, Daphne Strahl-Schäfer, Inken Blanca Post) and IXP (Eva Scholten) as well as the project partners within the university (Martin Alfuth, Jonas Klemp, Kerstin Zoell, Anne Schwarz-Pfeiffer, Ramona Nolden, Manuela Niemeyer, Nicolas Beucker, Dorothee Volker) for their constructive cooperation. The authors would also like to thank the voluntary participants for their contributions to the test series in order to create suitable records for our recognition tests.

References

[1] M. Krshiwoblozki, „IZM Fraunhofer," [Online]. Available: https://www.izm.fraunhofer.de/de/abteilungen/system_integrationinterconnectiontechnologies/arbeitsgebiete/motex-bandage.html. [Zugriff am 4. Oktober 2019].

[2] Noraxon MyoMotion, [Online]. Available: https://www.velamed.com/produkte/3d-inertialsensor-system. [Zugriff am 4. Oktober 2019].

[3] Project-KneTex, 2020. [Online]. Available: https://www.researchgate.net/project/KneTex.

[4] D. Felson, J. Niu, C. McClennan, B. Sack, P. Aliabadi, D. Hunter, A. Guermazi and M. Englund, „Knee Buckling: Prevalence, Risk Factors, and Associated Limitations in Function," in *Annals of internal medicine. 14*, 2007.

[5] H. Loose and K. Orlowski, „Gait patterns in standard scenarios: Using Xsens MTw inertial measurement units," in *6th International Conference on Research and Education in Mechatronics (REM)*, Bochum, 2015.

[6] F. Burget, C. Maurer, W. Burgard and M. Bennewitz, „Learning motor control parameters for motion strategy analysis of Parkinson's disease patients," in *IEEE/RSJ International Conference on Intelligent RobotsSystems (IROS)*, Hamburg, 2015.

[7] K. Kawano, S. Kobashi, M. Yagi, K. Kondo, S. Yoshiya and Y. Hata, „Analyzing 3D Knee Kinematics Using Accelerometers, Gyroscopes and Magnetometers," in *2007 IEEE International Conference on System of Systems Engineering*, 2007.

[8] J. Vince, Quaternions for Computer Graphics, Springer London, 2011.

[9] L. C. Tchakouté, L. Tremblay and B.-A. Menelas, „Response Time to a Vibrotactile Stimulus Presented on the Foot at Rest and During Walking on Different Surfaces," *Sensors,* Bd. 18, p. 2088, 6 2018.

[10] K. Herren and J. Kool, „Manuelle Geschicklichkeit: Nine-hole-peg Test (NHPT)," in *Assessments in der Rehabilitation, Band 1: Neurologie*, Bern, Verlag Hans Huber, Hogrefe AG, 2012.