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KneeHapp Textile: A Smart Textile System for Rehabilitation of Knee Injuries

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***Abstract*— Patients of an Anterior Cruciate Ligament (ACL) injury engage in a set of rehabilitation exercises to recover mobility and strength of their injured leg. We developed a smart bandage and user interface that provides live feedback to patients while exercising and computes a series of performance metrics used by orthopedists for assessment of the patient's recovery. The bandage uses smart textile components such as elastic conductive threads and snap buttons. We discuss how the smart textile components contribute to desirable properties of the bandage, such as robustness, washability and user comfort. Furthermore, we present a technique for calibrating the motion sensors on the bandage which is suitable for patients of ACL with limited mobility. Finally, we present the results of a controlled experiment with 10 patients with the goal to assess the accuracy of the bandage's measurements.**

I. INTRODUCTION

Tear of Anterior Cruciate Ligament (ACL) is a severe knee injury that occurs mostly among athletes. The rehabilitation after the injury can last as long as a year and often includes physical therapy, strength exercises and frequent visits to physiotherapists and doctors. Successful recovery of an ACL injury relies on the appropriate execution of rehabilitation exercises with the goal of recovering full range of motion, strength and coordination.

Currently, patients sustaining an ACL injury perform the rehabilitation exercises mostly unsupervised and lack quantitative ways to measure the quality and track performance of their exercising. Orthopedists also lack tools to assess patients' rehabilitation progress and still have to rely on subjective observations. Furthermore, orthopedists and patients meet at time intervals as long as three months and the treatment is decided upon observations during these meetings without consideration of the patient's recovery progress in the periods between visits.

In this paper, we introduce KneeHapp Textile, a smart compression bandage that supports different rehabilitation exercises performed by patients recovering from an ACL injury in order to recover flexibility and muscle strength. We address the construction and integration of textile sensors and connections and propose software solutions to quantify the progress of the rehabilitation after the ACL injury. We present KneeHapp's user interface on an iPad and Apple Watch.

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II. RELATED WORK

Different studies have investigated rehabilitation using wearables and mobile devices [5], [2]. In contrast, only a few studies have used smart textiles to support rehabilitation after an injury [3], [4], [1]. In addition, most of the research in the field of computer-assisted rehabilitation addresses injuries other than ACL. In contrast to other injuries (e.g. osteoarthritis), patients recovering from ACL injury are athletes that want to take up their training routines after recovery. As a consequence, the rehabilitation of an ACL injury involves a series of exercises to recover mobility and strength of the injured leg and to ensure the athlete is ready to go back to sports. We investigate the application of smart textile technologies to exercise-intensive rehabilitation processes.

III. REQUIREMENTS

Based on a series of interviews with two professional orthopedists who conduct ACL reconstruction surgeries on a daily basis, we identified a set of rehabilitation exercises performed by patients recovering from an ACL injury:

- *Knee bends*. After the surgery, patients perform mostly knee bends to recover mobility of their knees.
- *Squats*. During the first weeks after the surgery, patients suffer from muscular atrophy on the injured leg. A common exercise for strength recovery are knee squats and different variations of it.
- *One-leg hop*. Towards the end of the rehabilitation, orthopedists should assess whether patients are ready to start doing sports again. One-leg hop is an exercise in which patients should jump forward on one leg as far as possible and land stably.
- *Side hops*. Another exercise to assess patients performance and strengthen muscle is side hops. Side hops requires patients to hop side-wise on one leg over a distance of 20-30 cm during a period of 10 to 60 seconds.

IV. KNEEHAPP

KneeHapp measures the performance and provides live feedback to patients while performing different ACL rehabilitation exercises. The KneeHapp system consists of a smart compression bandage, an iPad App. The smart compression bandage acquires and processes sensor data and delivers the computed results to the iPad App via Bluetooth Low Energy. The iPad App displays live feedback about the quality of the rehabilitation exercises and keeps track of the rehabilitation performance. An additional interface on the Apple Watch lets

Fig. 1: Outer layer (left) and inner layer (right) of the KneeHapp bandage.

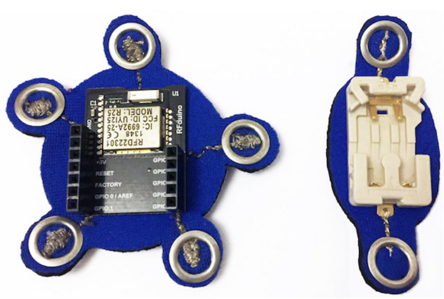

Fig. 2: Smart textile patches hosting a microcontroller (left) and a battery holder (right).

patients to control specific parameters during an exercising session.

A. Smart Textile Bandage

We adapted a conventional compression bandage used by patients to reduce swelling after a knee surgery. We used this compression bandage as a substrate for integration of electronics. The outer side of the bandage hosts two motion sensors, two microcontrollers and a coin cell battery holder. The inner side contains an electric circuit made of elastic conductive threads. An additional sleeve in the inner side protects the circuits from sweat and can be removed for washing purposes. Figure 1 shows outer and inner layers of the bandage.

We decided to connect the electronics to the electric circuit using elastic conductive thread based on three main design goals: robustness, user comfort and low energy consumption. Elastic conductive threads are less prone to snapping when compared to other materials to connect electronic devices such as conventional cables or conductive thread. This is of particular relevance because connections laid along the knee are prone to a considerable amount of strain while patients perform exercises involving knee bends. We also considered a design involving two separate microcontroller units that transmit data wirelessly. We discarded this design because the need for wireless data transmission to synchronize the signals produced by upper and lower microcontroller units would increase energy consumption rates considerably. Furthermore, conductive threads do not constrain user movements more than the actual bandage.

All conventional electronic elements are sewn on smart textile patches and equipped with snap buttons as conductive contacts to the main bandage. This enables users to remove the electronics for replacement or washing purposes. Figure 2 shows two smart textile patches.

B. Software Computations

KneeHapp supports different rehabilitation exercises. This section describes how KneeHapp processes data from the aforementioned sensors in order to provide feedback to patients while exercising and compute performance metrics that can be tracked over time.

1) Range of Motion: KneeHapp calculates the angle of flexion of the leg based on the Euler angles computed by lower and upper IMUs. KneeHapp supports two calibration approaches. By convention, the angle of flexion of the leg is equal to zero when the leg is relaxed on a flat surface. Therefore, one calibration approach supported by KneeHapp determines the sensor alignment while patients extend their leg on a flat surface. However, most patients are not able to fully extend their leg after the surgery. In order to address this issue, we considered different calibration approaches proposed in the literature, including pose (i.e. users perform a predefined pose) and functional (i.e. users perform specific movements) calibration. But since patients might not be able to perform specific poses or movements after surgery, we devised a novel calibration approach that consists of three steps:

1) Wear the bandage on the healthy leg and measure the orientation of the IMU while the leg is laid on a flat surface.
2) Measure the angle of flexion while the leg is slightly bent by placing the back of the knee on top of any object. This provides a calibration offset.
3) To 'transfer' the calibration offset to the injured leg, the user should wear the bandage on the injured leg and measure the angle of flexion while placing the back of the knee on top of the same object.

These steps are illustrated in Figure 3. Because the angle of flexion is measured on top of the same object for both legs, the angle of flexion for both legs is, by definition, the same. The difference between the measured angles of flexion is used as an offset and added to the angles measured on the injured leg. This calibration approach does not require additional equipment such as wedges or individuals who perform the measurements. KneeHapp provides visual feedback live to patients about their current angle of flexion and about the maximal angles of flexion, extension, and hyper-extension (i.e. extending a limb over 180°) of the leg, as shown in Figure 4.

2) One-leg Squat: KneeHapp provides live feedback to patients while performing one-leg squats in three ways. First, it calculates the angle of flexion of the leg during the squat and triggers a visual and auditive feedback when patients

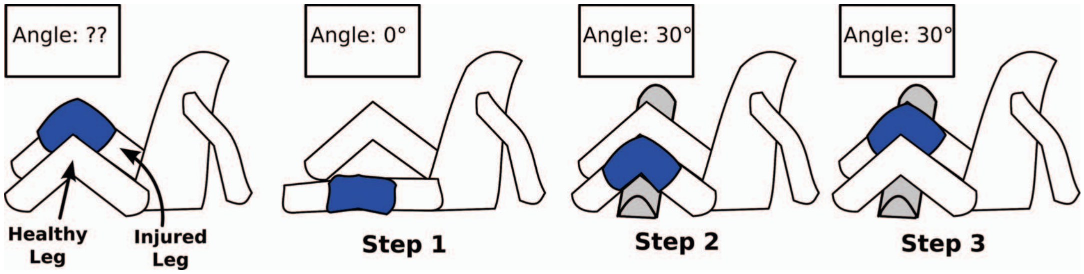

Fig. 3: Illustration of our calibration procedure with an example. In step 1, KneeHapp is calibrated on the healthy leg, which the patient can extend on a flat surface. In step 2, KneeHapp calculates the angle of flexion while the leg is placed above an object. In step 3, KneeHapp assumes the angle of flexion of the injured leg is the same as on the healthy leg when placed on the same object. After step 3, patients can begin to calculate the range of motion of their injured knee.

achieve a squat angle of 60°. Second, it computes the degree of medial collapse of a patient's knee and warns patients in case they reach a threshold of 10°. Third, it computes the degree of shaking of the leg, which is computed as the standard deviation of the magnitude of the linear acceleration produced by the IMUs.

3) One-leg Hop: KneeHapp measures and keeps track of the performance of one-leg hops by comparing the duration of the hop done with each leg. This is done in two steps. First, a second order Butterworth low-pass filter is applied to reduce noise in the signal acquired by the upper motion sensor with a $cutoff = 15Hz$. Second, the different phases of the jump (i.e. jumping, flying, landing) are estimated using a pre-established set of thresholds calibrated to each phase.

4) Side Hops: KneeHapp counts the number of side hops performed by patients in a configurable period of time. This is done in three steps: *preprocessing*, *detection* and *disambiguation*. In the *preprocessing* step, the linear acceleration along the vertical and forward axes are filtered using a Resistor-Capacitor (RC) low-pass filter with a time constant $\tau = 0.25$. Usually, each hop performed by the user produces a high and a low peak in the signal. The *detection* step uses a peak detection algorithm to count the number of high and low peaks in the filtered signal. In order to avoid counting bumps caused when patients do not land stably after a hop, KneeHapp ignores peaks with a distance smaller or equal to 15 samples to a previously detected peak. The *disambiguation* step compares the number of lower and upper peaks detected and returns the median.

C. User Interface

KneeHapp's user interface is displayed on an iPad and Apple Watch. The iPad enables patients to keep track of their rehabilitation progress and provides live feedback while exercising. Figure 4 shows a screenshot of the iPad interface displaying the angles of flexion, extension and hyperextension computed by KneeHapp.

The interface on the Apple Watch enables patients to start and stop the exercises and provides feedback about the quality of the performed exercises. Starting and stopping exercises directly from the wrist is convenient at the beginning of the rehabilitation because patients might have limited mobility and towards the end because patients perform squats and jump-based exercises. The interface on the Apple Watch also displays exercise countdowns, angles of flexion of the leg and indicates when specific angles have been reached (e.g. medial collapse) by means of vibrations and sound. Figure 5 shows two screenshots of the interface on the Apple Watch for the *Range of Motion* and *Squat* exercises.

Fig. 4: iPad App displaying the *Exercises* tab. The *Exercises* tab provides live feedback about the performance of the selected exercise.

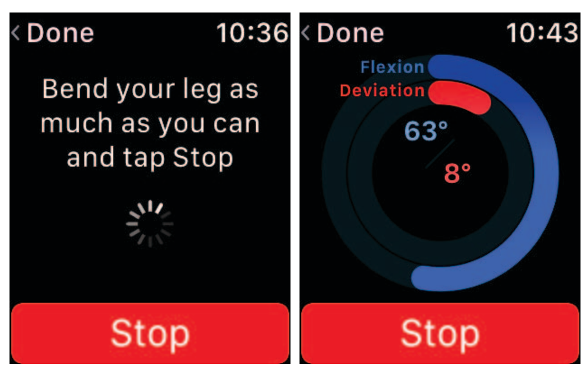

Fig. 5: Interface on the Apple Watch displaying instructions to start the range of motion measurement (left) and the computed angles during a squat (right).

TABLE I: Answers to a usability questionnaire given to patients. -2: *Strongly disagree*; -1: *Disagree*; 0: *Neutral*; +1: *Agree*; +2: *Strongly Agree*.

	-2	-1	0	+1	+2
KneeHapp provides me with helpful information during the Range of Motion exercise	0	0	0	2	3
KneeHapp provides me with helpful information during the One-Leg Squat exercise	0	0	0	3	2
KneeHapp helps me to perform the One-Leg Squat exercise correctly	0	0	0	4	1
The iPad and Watch App were easy to use	0	0	0	4	1
The bandage was comfortable to wear	0	0	1	3	1
KneeHapp would motivate me to perform my rehabilitation exercises	0	0	1	1	3
I would use KneeHapp	0	0	0	3	2

V. Controlled Experiment

We evaluated the accuracy of the computations performed by KneeHapp in a controlled experiment where we collected sensor data from 10 patients (3 female, 7 male, age range: 20-26, one of them was 51 years old) at different stages in the recovery after an ACL injury while performing the following exercises: range of motion measurements, one-leg hops and side-hops, as follows:

1) Range of Motion: We calibrated KneeHapp with our calibration approach and measured four different angles of flexion per leg. In total, we measured 80 angles. We considered three approaches to obtain reference angles of flexion. In contrast to other studies, we decided not to use a goniometer as reference because measurements taken from goniometers are subjective to each observer [6]. Another approach we considered was placing point markers at the ankle, knee and hips to reconstruct the actual positions of the bones. However, we discarded this approach because of the difficulty to locate specific bones accurately on some subjects due to muscle and fat. We decided to align straight markers along the subject's upper and lower leg and calculated the angle between the markers digitally on a 2D photograph. The angles of flexion calculated by KneeHapp correlated to the reference angles with an average error of 4.82°(± 3.92°). These results suggest KneeHapp provides more accurate measurements than goniometers, which have been shown to have an average intra-observer variability of 9.6°[6].

2) One-leg Hop: We asked subjects to perform a total of six hops (a short hop, a middle hop and a long hop, once on each leg). We collected a total of 60 hops. We placed a camera at ground level and recorded jumps at 240 frames per second. We determined the duration of each hop by counting the amount of frames elapsed between jumping and landing in the video recordings. We considered as a jumping frame the first frame in which the subject's foot was not in contact with the ground anymore and landing frame as the first frame where the foot made contact with the ground again. We measured the absolute difference between the calculated duration and the reference duration and normalized the difference by the reference duration. KneeHapp detected jump durations with an average accuracy of 77.10% (± 18.57%).

3) Side Hops: We asked subjects to perform as many side hops as they could in a period of 10 seconds. In order to capture the differences in strength and motoric skills between individuals' primary and secondary legs, subjects performed side hops on both legs. We collected a total of 395 hops. In order to obtain reference values, we counted and video-recorded the hops performed by the subjects. KneeHapp computed the amount of side-hops performed by subjects with an average accuracy of 96.8% (± 22%).

We evaluated the squat exercise qualitatively together with the usability of KneeHapp in a series of interviews with patients of an ACL injury. We improved KneeHapp with the insights gained during these interviews and handed in a questionnaire at the end, which is shown in Table I.

The results presented in this section meet the accuracy requirements of a system to support the rehabilitation after an ACL injury, as they are meant to aid orthopedists to make treatment decisions. In particular, a performance score for each leg could be computed based on several repetitions of the assessment exercises. The improvement of this score over time together with the score attained when performing the exercises with the non-injured leg could be provided to orthopedists to support them at making treatment decisions.

VI. Conclusion

We presented KneeHapp Textile, a smart textile system that supports different rehabilitation exercises performed throughout the rehabilitation of an ACL injury. The results of our controlled experiment suggest that KneeHapp Textile computes the different exercise performance metrics reliably. Therefore, KneeHapp can be used by patients to obtain live feedback about the execution of the exercises (e.g., shaking and deviation during a squat) and by orthopedists to make better-informed treatment decisions.

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